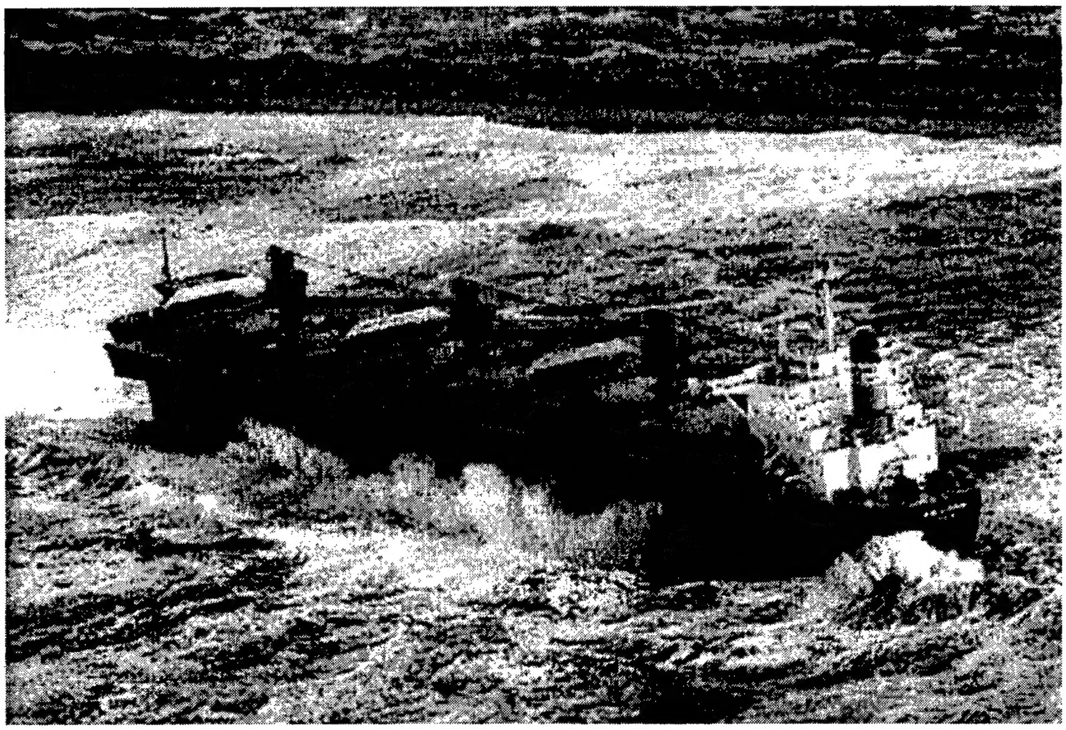
ABS Rules versus Reliability Based Design of Bulk Carriers



A Comparative Analysis of Ship Design Approaches

by
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LRFD Reliability versus ABS Design Comparison

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Abstract: This paper presents a comparison of the ABS Rules approach for ship design to the recently developed LRFD Reliability Based Design approach. Three elements of the design process are used for comparison. These are the Bottom Plating Thickness, the Bottom Longitudinal Section Modulus and the Hull Section Modulus. The development of the calculations is shown to help understand how the results are achieved. The results are compared in various configurations, which are included in the appendices for reference. The comparisons are evaluated with regard to how well the LRFD results compare to the ABS results for different design criteria. Conclusions are made concerning the relevance of these comparisons to the effort of advocating a move towards LRFD Reliability Based Design procedures. Finally, software development is discussed with a view to the future acceptance of the new approach and the initiation of a transition to LRFD Reliability Based Design procedures.

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Cover Photo: From Ship Structure Committee Website: Bulk Carrier, NEW CARISSA, aground near Coos Bay, Oregon, February 4, 1999.

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Chapter 1

Introduction

1.1 Project Mission Statement

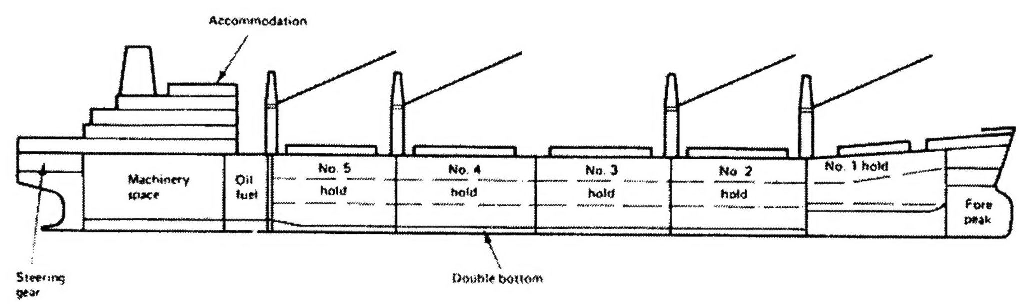
This paper consists of a comparison of results from using two different approaches in the design of bulk carriers. The first method uses the ABS rules, which have been the corner stone for Naval Architecture for decades. The second method is a new approach to ship design using reliability methods as developed by Mansour (2002). The results will be compared to find out if they match closely enough to demonstrate a valid calibration point between the two methods, such that a transition towards the reliability method may progressively be developed.

1.2 Bulk Carrier Construction

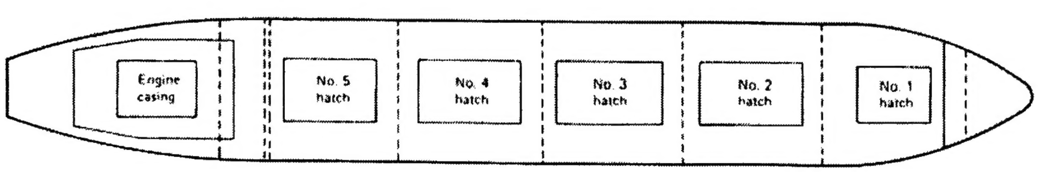
This section is focused on the non-naval architect audience, and can be overlooked by any reader with ship building background. In order to set a framework for the following discussions, some understanding of how bulk carriers are built, will give the lay-reader a better appreciation of the motivation towards a reliability based design approach.

Although they might all look the same to the untrained eye, the huge merchant ships that travel the World's oceans are quite different when viewed from a design and construction perspective. In general, they can be divided up into categories based on the

type of cargo that they will transport for the duration of their service life. The two cargo types that come to mind typically when considering cargo ships are tankers and bulk carriers. These two types require different design and construction methods, due to the difference in the cargo type, the former being free liquid or gas pumped into the hold and the latter, described by Taylor (1992) as a single commodity cargo such as grain, sugar and ores in bulk. Since these cargo types cause different load distributions in the ship's holds, it is important to consider them separately. This paper will concentrate specifically of certain design aspects of bulk carriers. Other types of merchant ship studies can be found elsewhere, and are only mentioned to highlight the difference of various types of merchant ships and the relevance of independent study and design code formulation for each.



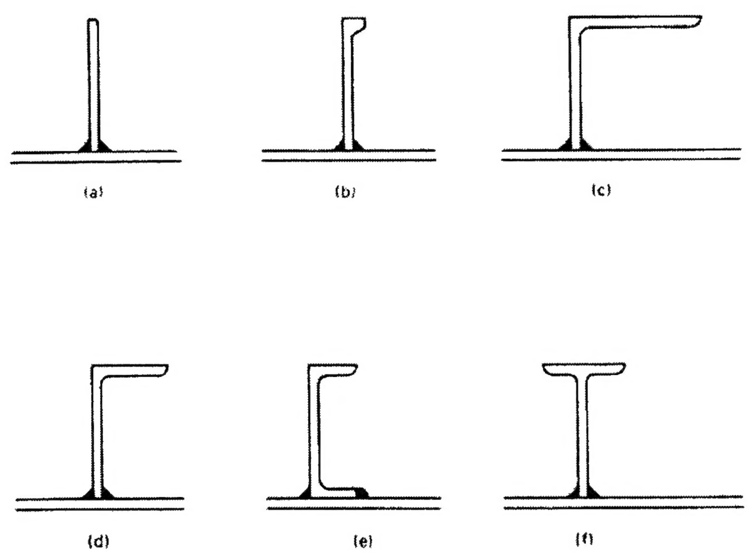
(a) Elevation



(b) Plan

Figure 1.1. Elevation and Plan views of a typical Bulk Carrier

Bulk carriers are generally divided into a number of holds of various configurations which are accessed by big hatches on the ship's main deck. Figure 1.1 shows a typical Bulk Carrier layout. One important thing to note in this diagram is the double bottom along the base or keel of the vessel. This provides added strength to the ship's hull so that it can withstand the loads applied by the cargo from the inside, and the sea loads imposed by the ocean environment on the outside. The double bottom is made up of the bottom plate, which is the outer skin of the ship and the inner-bottom plate, on which is what the cargo sits. The two plates are separated by girders which run in both transverse and longitudinal directions. There are still large areas of plate between the girders, and due to the natures of the loads experienced, they need some extra support. This is achieved by the introduction of stiffeners on both plates which are called longitudinals since they run along the length of the ship.



(a) flat plate; (b) offset bulb plate; c) equal angle; d) unequal angle; e) channel; f) tee

Figure 1.2. Types of Longitudinals

These longitudinals are found in various shapes and sizes as shown in Figure 1.2, but they are basically small beams attached directly to each plate.

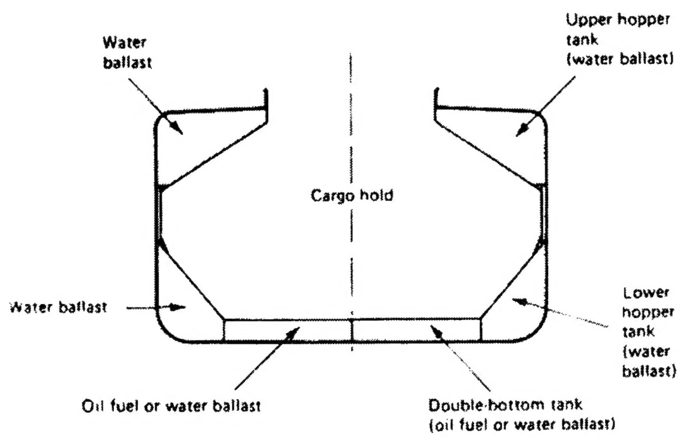


Figure 1.3. Transverse Section

Figure 1.3 shows a transverse section of a typical solid commodity cargo bulk carrier, illustrating that most of the ship's cross sectional area is available for filling with cargo, with the exception of the corner areas which have water ballast tanks, which run the length of the ship. These tanks are used to help control the location of the ship's center of gravity with respect to the ocean. For example, if a ship was carrying a relatively light cargo, the captain might have to fill the ballast tanks completely to ensure that the ship sits low in the water, thereby reducing the potential for capsizing. Conversely, a heavy cargo such as ore, might sit at the same attitude, but with empty ballasts tanks.

1.3 Classification Societies

A classification society is an organization which categorizes ships designed and built by their specific rules and specifications, with respect to their seaworthiness. These

societies are found all over the world, and strive to ensure safe passage of the crews and their cargoes by instituting standards which reduce the risk of failure of those vessels that choose to undergo an evaluation of their seaworthiness.

Taylor (1992) lists some of these societies along with their respective countries which include:

- Lloyd's Register of Shipping (UK)
- American Bureau of Shipping (USA)
- Bureau Veritas (France)
- Det Norske Veritas (Norway)
- Germanischer Lloyd (Germany)
- Registro Italiano (Italy)
- Nippon Kaiji Kyokai (Japan)

These societies work at classifying the ship's registered in their respective countries, but they discuss items of common interest through an international forum called the International Association of Classification Societies (IACS). As mentioned earlier, this report is working towards improving the methods used by the American Bureau of Shipping (ABS) for ship construction by incorporating a reliability approach, which will allow designers to better quantify uncertainties and biases associated with design parameters.

1.4 Steel Design Agencies

Within the United States, there are a number of different steel design agencies, each with their own rules, guidelines and recommendations on how to approach steel

design for their specific construction project interests. Part of the work done by Mansour (2002) was to review the different reliability based code formulations of these agencies in an effort to find background information for the new reliability approach to ship design. Some of the design agencies that were reviewed include:

- American Petroleum Institute API)
- American Institute of Steel Construction (AISC)
- Comite Euro-International du Beton (CEB)
- National Building Code of Canada (NBC)

Chapter 2

Background

2.1 Historic developments

Although the ABS Rules have been a main stay in Naval Architecture for a very long time, they are somewhat limiting based on what is known today in the areas of consideration of the multitude of forces of various magnitudes and frequencies, which act upon a ship's hull as it moves through the water. This is an important factor for advocating reliability methods in determining member sizes. It has been said that some of the biggest problems in design come from not understanding the correct loading of members and the effect of these loads on the member. The use of reliability methods not only brings added value to help the designer determine the loads more correctly, but it also allows the designer to assign levels of uncertainty to each discrete load situation.

In his development of reliability methods for the design of ship hull members, Mansour (2002) examined many existing codes, including, API, AISC, CEB and NBC and determined that reliability in ship hull member design could be represented best using a Load and Resistance Factor Design (LRFD) Approach. He suggested the development of a new version of the ABS SafeHull Rules, which would be based on LRFD procedures. A good example of the reasoning behind this suggestion was that the SafeHull standard did not account for the dependence of partial safety factors, which

produce a constant reliability based on the ratio of the design wave bending moment to the stillwater bending moment.

The consideration of the use of LRFD criteria as a calculation vehicle for reliability methods is important, in that it follows the lead of civil and structural engineers all over the world, who are transitioning to LRFD from the old ways of limit state design. Of course, like everything else, not everybody is taking that step as some are too set in their ways, but it is reasonable to say that LRFD is the future of steel design, whether it is a structural engineer designing a steel skeleton for a sky scraper or a Naval Architect designing the bilges of a bulk carrier or oil tanker.

A comparison of LRFD approach with the ABS SafeHull standard methods, which are based on Limit State Design methods, will give the reader more confidence of the added value brought to the design table by using the LRFD methods. For this study, the comparison shall be drawn between the two methods in the case of the following:

- Bottom Plate Thickness
- Bottom Longitudinal Section Modulus
- Ship Hull Section Modulus

2.2 Limit State Design Vs. LRFD

A comparison or Limit State Design methods and Load and Resistance Factor Design methods will demonstrate the inherent added value of adopting the latter as the way forward in Ship Hull Design.

Limit State Design methods call for the establishment of the Ultimate Limit State of Loadings that can be applied to a vessel, and then, the vessel's capacity is defined

based on that condition. This method provides no factor of safety between the maximum load and the maximum capacity, and since a 10,000-year life span is often used as design criteria, this can cause major over design in ship's structures, which is uneconomical, especially in these times of recession.

LRFD methods call for safety factors to be applied to both the design load (typically considering a 100-year lifespan), and the design capacity. Basically, the design load is factored up and the design capacity is factored down. Figure 2.1 shows a good representation of the differences between the two methods.

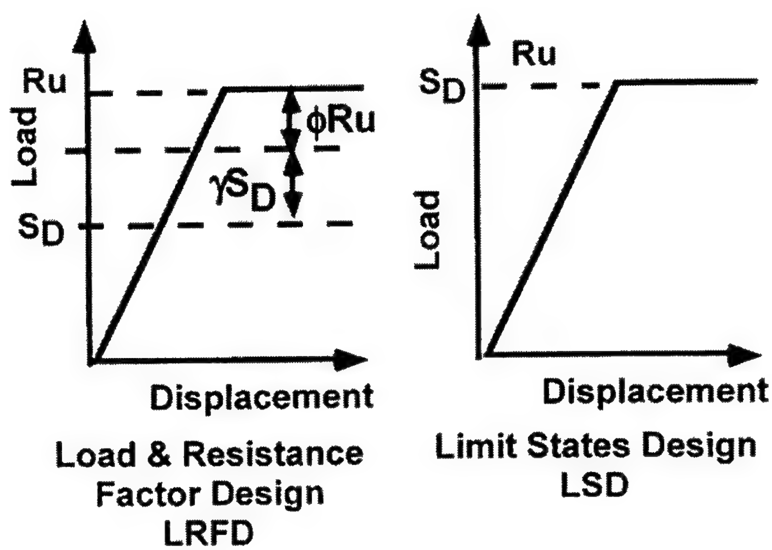


Figure 2.1. LRFD and LSD design formats

The development of a ship hull design format based on LRFD methods brings a more realistic approach to ship building, which will bring savings that can be channeled into technology advances due to the lower occurrence of over designed members.

2.3 Simplified Reliability Theory

The calculation of values for the probability of failure, and associated safety or reliability index for any of the elements of ship design are beyond the scope of this paper, but they are worth brief explanation to help develop an understanding of their relevance to ship design and to LRFD design methods.

Each element of a structure that is designed and built has a risk, or probability of failure, however slight that may be. Reliability theory attempts to quantify this in a meaningful way that can be used by design engineers to understand the risks involved during certain conditions, or over certain timelines, throughout the life of the structure.

Using probabilistic techniques, the applied load and the strength of a structure are considered to be independent random variables with certain probability distributions, which have mean values and standard deviations. The safety/reliability index (β) is the division of the combination of the mean values for the applied load and the strength by their combined standard deviations. The probability of failure (Pf) is then a function of this reliability index.

This explanation has been greatly simplified for the lay reader, so that when these issues are discussed later in the paper, he/she can follow along with some basic level of understanding.

Chapter 3

Analyses

3.1 ABS SafeHull standard Methods

3.1.1 Bottom Plate Thickness

According to the ABS Rules (Part V, 2000) the bottom plate net thickness (t_n) cannot be less than t_1, t_2 or t_3, which are given by the following formulae:

$$t_1 = 0.73s(k_1 p / f_1)^{1/2} (mm)$$

$$t_2 = 0.73s(k_2 p / f_2)^{1/2} (mm)$$

$$t_3 = cs(Smfy / E)^{1/2} (mm)$$

For this analysis, only the values of t_1 and t_2 will be compared, and the same formula for t_3 will be used for both ABS and LRFD, since it already uses the yield strength of steel directly to calculate plate thickness.

3.1.1.1 Calculation of t_1

$$t_1 = 0.73s(k_1 p / f_1)^{1/2} (mm)$$

s = Transverse spacing between longitudinals (meters)

$k_1 = 0.342$

p = Nominal pressure exerted on hull plate (N/mm^2)

f_1 = permissible stress (N/mm^2); for values of Sm and fy, see Table A-2-2

For demonstration purposes, a sample scenario will be examined to show how the results are reached, then similar calculations will be done for all other examples as

discussed later in this chapter. The sample parameters are as follows for the calculation of t_1:

Ship draft (*d*) = 34.3 m; Longitudinal Spacing (*s*) = 1.0 m; Material = H36 Grade Steel

Variables

$k_1 := 0.342$

$s := 1.0m$

Using Load Case A of Appendix 2 for example:

$pi := 1.9970 \frac{kgf}{cm^2}$ $\quad pe := 0.7110 \frac{kgf}{cm^2}$

$g = 9.807 \frac{m}{s^2}$

$d := 13.43m$

Nominal Pressure of Water on Hull

$p := |pi - pe|$

$$\boxed{p = 12.611 \frac{N}{cm^2}}$$

Permissible Bending Stress

For H36 Steel, $Sm := 0.908$ and $fy := 355 \frac{N}{mm^2}$

For Load Case A, $k_3 := 0.4$

Minimum $f_1 := k_3 \cdot Sm \cdot fy$

$$\boxed{f_1 = 128.936 \frac{N}{mm^2}}$$

Bottom Plate Thickness (t_1)

$$t_1 := 0.73 \cdot s \cdot \left(\frac{k_1 \cdot p}{f_1}\right)^{\frac{1}{2}}$$

$$\boxed{t_1 = 13.351\,mm}$$

3.1.1.2 Calculation of t_2

$t_2 = 0.73s(k_2 p / f_2)^{1/2}(mm)$

s = Transverse spacing between longitudinals (meters)

k_2 = 0.500

p = Nominal pressure exerted on hull plate (N/mm^2)

f_2 = permissible stress (N/mm^2); for values of *Sm* and *fy*, see Table A-2-2

Table 3.2 shows values of t_2 for all reasonable values of s, p, and f_1. For demonstration purposes, a sample scenario is followed below. This is the basis for all calculations. The sample parameters are as follows:

Ship draft (d) = 34.3 m; Longitudinal Spacing (s) = 1.0 m; Material = H36 Grade Steel

Variables

$k_2 := 0.500$

$s := 1.0m$

Using Load Case A of appendix 2 for example

$pi := 1.9970 \frac{kgf}{cm^2}$ $\quad pe := 0.7110 \frac{kgf}{cm^2}$

$g = 9.807 \frac{m}{s^2}$

$d := 13.43m$

Nominal Pressure of Water on Hull

$$p := |pi - pe|$$

$$\boxed{p = 12.611 \frac{N}{cm^2}}$$

Permissible Bending Stress

For H36 Steel, $Sm := 0.908$ and $fy := 355 \frac{N}{mm^2}$

$$f_2 := 0.8 \cdot Sm \cdot fy$$

$$\boxed{f_2 = 257.872 \frac{N}{mm^2}}$$

Bottom Plate Thickness(t₂)

$$t_2 := 0.73 \cdot s \cdot \left(\frac{k_2 \cdot p}{f_2} \right)^{\frac{1}{2}}$$

$$\boxed{t_2 = 11.415\,mm}$$

3.1.1.3 Calculation of t_3

$$t_3 = cs(Smfy / E)^{1/2} (mm)$$

Variables

For H36 Steel, $Sm := 0.908$ and $fy := 355 \frac{N}{mm^2}$

$E := 20.6 \cdot 10^6 \cdot \frac{N}{cm^2}$

For H36 Steel, material conversion factor $Q := 0.72$

Note: Minimum value for c is $0.4*Q^{0.5}$: $c := 0.4 \cdot Q^{0.5}$

$c := 0.339$

Bottom Plate Thickness (t_3)

$$t_3 := c \cdot s \cdot \left(\frac{Sm \cdot fy}{E} \right)^{\frac{1}{2}}$$

$$\boxed{t_3 = 13.41\, mm}$$

These results for the bottom plate thickness are presented later in the summary of calculations, where they can be compared to the corresponding LRFD results.

3.1.2 Bottom Longitudinal Section Modulus

The section modulus of the bottom longitudinals within 0.4*L* amidships is given by the following formula according to ABS rules:

$SM = M / f_b (cm^3)$

M is the longitudinal bending moment which is calculated as follows:

$M = 1000cpsl^2 / k(N \cdot cm)$ (Formula is based on entering the variables in the given units)

c = 1.0 without struts, or c = 0.65 with effective struts

p = Nominal pressure exerted on hull plate (N/cm^2)

s = Transverse spacing between longitudinals (in mm)

l = Span of longitudinals between effective supports (in m) = 2.5 meters

k = 12

> *Note:* Since the bottom longitudinals outboard of 0.3*B* from the mid-ships center-line have additional requirements, this analysis will focus only on the longitudinal members within 0.6*B* amidships.

Continuing with the example scenario, the sample parameters used in calculating the bottom plate thickness will be used, with the additional variables as needed. Members will be considered without struts, i.e. $c = 1.0$

3.1.2.1. Calculation of ABS Bottom Longitudinal Section Modulus

Variables

$$c := 1.0$$

$$p := 12.611 \frac{N}{cm^2}$$

$$s := 1000mm$$

$$l := 2.5m$$

$$k := 12$$

Bending Moment

$$M := \left(\frac{1000 \cdot c \cdot p \cdot s \cdot l^2}{k} \right)$$

$$\boxed{M = 6.568 \times 10^6 N \cdot cm}$$

Bending Stress

For H36 Steel, $Sm := 0.908$ and $fy := 35500 \frac{N}{cm^2}$

$$f_b := 0.55 \cdot Sm \cdot fy$$

$$\boxed{f_b = 1.773 \times 10^4 \frac{N}{cm^2}}$$

Longitudinal Section Modulus

$$SM := \left(\frac{M}{f_b} \right)$$

$$\boxed{SM = 370.486 cm^3}$$

This result will be compared to the corresponding LRFD result in the summary section, later in this chapter. Also further comparisons are shown in Appendix 4, and Chapter 4 will provide discussion of what these results mean.

3.1.3 Hull Section Modulus

To appreciate the idea of the section modulus of the ship's hull, it is best to imagine modeling the ship as a steel beam. However, what makes a ship's section modulus a little more complex than a beam is the variation of forces exerted by the ocean throughout its length. The hogging or sagging forces of the waves has a varied and opposing effect on the hull, so the greater of the two shall be considered as the maximum load for both hogging and sagging directions.

Following the sample scenario, the parameters for a typical Bulk Carrier provided by ABS as shown in Appendix 1 will be used in calculating the Hull Section Modulus. The Section Modulus for the Hull (*SM*) considers the section of 0.4*L* amidships as the shape of the ship, within that part of the ship's length as essentially close to rectangular, like a box girder. This is seen to be the best choice of dimension for the modeling of the ship as a beam, to determine the order of magnitude of hull section modulus that will be calculated, given different conditions and variations.

From the ABS Rules, the following equation applies for calculating the Hull Section Modulus:

$$SM = M_t / f_p (m \cdot cm^2)$$

$M_t = M_{sw} + M_w$, the algebraic sum of the still-water bending moment and the wave induced bending moment.

f_p =Nominal permissible bending stress, given by ABS Rules = 17.5 *KN/cm²*

The minimum allowable Section Modulus being given by the equation:

$SM_{\min} = C_1 C_2 L^2 B(C_b + 0.7)(m \cdot cm^2)$

3.1.3.1 Calculating the Total Vertical Bending Moment (M_t)

The total vertical bending moment is the maximum of the hogging or sagging bending moments, which are the algebraic sum of their respective still-water bending moments and wave induced bending moments. For this analysis, the hogging and sagging still water bending moments will be those provided by ABS with the sample ship data for Bulk Carrier D as illustrated in Appendix 1.

Next, consider the maximum wave-induced bending moment (M_w). This is the greater of the sagging moment (M_{ws}) or the hogging moment (M_{wh}) amidships:

$M_{ws} = -k_1 C_1 L^2 B(C_b + 0.7)(KN \cdot m)$

k_1 = 110 per ABS Rules for SI system

C_1 = 10.75 – (300-L/100) if (90m $\leq$ L $\leq$ 300m)

= 10.75 if (300m < L < 350m)

= 10.75 – (L-350/150) if (350m $\leq$ L $\leq$ 500m)

L = Length of vessel on summer load line (from fore sides of stem to center-line of rudder stock)

B = Breadth of vessel (greatest molded breadth)

C_b = Block Coefficient at summer load line based on L

$M_{wh} = +k_2 C_1 L^2 B C_b \times 10^{-3}(KN \cdot m)$

k_2 = 190 per ABS Rules for SI system

3.1.3.2. Calculation of the ABS Hull Section Modulus

Variables

$LBP := 128.4$

$L := LBP \qquad L := 128.4$

$C_1 := 10.75 - \left(\frac{300 - L}{100}\right)^{1.5} \qquad C_1 := 8.502$

$k_1 := 110$

$k_2 := 190$

$B := 23$

$C_b := 0.794$

Wave Induced Bending Moments, Sagging (s) & Hogging (h)

$Mws := -k_1 \cdot C_1 \cdot L^2 \cdot B \cdot \left(C_b + 0.7\right) N \cdot m \qquad Mws := -5.298 \cdot 10^8 \cdot N \cdot m$

$Mwh := k_2 \cdot C_1 \cdot L^2 \cdot B \cdot C_b \cdot N \cdot m \qquad Mwh := 4.864 \cdot 10^8 \cdot N \cdot m$

Still-water Bending Moments, Sagging (s) & Hogging (h)

$Msws := -202000 \cdot 10^3 N \cdot m$

$Mswh := 367000 \cdot 10^3 N \cdot m$

Total Vertical Bending Moments, Sagging (s) & Hogging (h)

$Mts := Msws + Mws \qquad Mts = -7.318 \times 10^8 N \cdot m$

$Mth := Mswh + Mwh \qquad Mth = 8.534 \times 10^8 N \cdot m$

$Mt := Mth$

Design Hull Section Modulus (SM)

$$Mt = 8.534 \times 10^{8} N \cdot m$$

$$fp := 17.5 \cdot 10^{3} \cdot \frac{N}{cm^{2}}$$

$$SM := \frac{Mt}{fp} \qquad SM = 4.877 \times 10^{4} cm^{2} \cdot m$$

For H36 Steel, SM is requced by a factor ofQ = 0.72

$$SM_{36} := 0.72 \cdot SM \qquad \boxed{SM_{36} = 3.511 \times 10^{4} cm^{2} \cdot m}$$

This result will be presented in a bar chart format and compared to the LRFD example later in this chapter.

This completes the ABS examples of the design sections being compared in this paper. The next section will develop the calculations of the corresponding LRFD results so that comparison of the two design approaches can be made.

3.2 LRFD Reliability Approach.

In the application of LRFD methods to a calculation, the load (*S*) and capacity (*R*) formulation can be simplified as follows:

$$\gamma \cdot S \leq \phi \cdot R$$

where γ is the load factor (usually greater than unity), and φ is the resistance factor associated with the capacity (usually less than unity).

The determination of these factors is an important part of the approach development. The factors themselves help account for uncertainties and biases which cause variations in the loads and capacities. They are also a function of the design decision related to the desired reliability for the expected life span of the vessel (100 year, 1000 yr, etc.). For this analysis, the factors developed by Mansour (2002) will be applied for the various types of steel for comparison with the ABS results. Later, an attempt will be made to derive the factors independently from first principles.

3.2.1 Bottom Plate Thickness

In developing the LRFD approach, Mansour (2002) incorporated the load and resistance factors as follows (using the formula of t_1 for illustration):

$$t_1 = 0.73s\left(\frac{k_1\gamma_p \cdot p_n}{\phi \cdot f_y}\right)^{1/2}$$

where, p_n and f_y are random variables representing the nominal pressure (load) and the yield strength of steel (capacity) respectively. Table A-4-1 and Table A-4-2 give the γ and φ factors associated with the various grades of steel for t_1 and t_2, respectively.

3.2.1.1 Calculation of t_1

$$t_1 = 0.73s\left(\frac{k_1\gamma_p \cdot p_n}{\phi \cdot f_y}\right)^{1/2}$$

Variables

$k_1 := 0.342$

$s := 1.0m$

Using Load Case A of Appendix 2 for example:

$pi := 1.9970 \frac{kgf}{cm^2} \qquad pe := 0.7110 \frac{kgf}{cm^2}$

$g = 9.807 \frac{m}{s^2}$

$d := 13.43\,m$

Nominal Pressure of Water on Hull

$p := |pi - pe|$

$$\boxed{p = 12.611 \frac{N}{cm^2}}$$

Yield Strength of Steel and Partial Safety Factors

For H36 Steel, $fy := 355 \frac{N}{mm^2}$

$\gamma := 2.83$

$\phi := 1.03$

It is worth noting here that the φ value is greater than unity for the above partial safety factor. This is the result of the method used to develop the partial safety factors. The φ presented above includes a factor of 1.2 which was used to normalize the mean

value of the yield strength of steel, when the partial safety factors were being developed by Mansour (2002). The partial safety factor used for that LRFD approach development was less than unity, as one would expect. This explanation applies equally to any other mention of φ values that are greater than unity throughout the remainder of this paper. This will also be discussed further in the evaluations and conclusions chapter.

Bottom Plate Thickness (t_1)

$$t_1 := 0.73 \cdot s \cdot \left(\frac{k_1 \cdot \gamma \cdot p}{\phi \cdot fy} \right)^{\frac{1}{2}}$$

$$\boxed{t_1 = 13.338\,mm}$$

3.2.1.2 Calculation of t_2

$$t_2 = 0.73 s \left(\frac{k_2 \gamma_p \cdot p_n}{\phi \cdot f_y} \right)^{1/2}$$

Variables

$k_2 := 0.500$

$s := 1.0m$

Using Load Case A of appendix 2 for example

$pi := 1.9970 \frac{kgf}{cm^2}$ $\quad pe := 0.7110 \frac{kgf}{cm^2}$

$g := 9.807 \frac{m}{s^2}$

$d := 13.43m$

Nominal Pressure of Water on Hull

$$p := |pi - pe|$$

$$\boxed{p = 12.611 \frac{N}{cm^2}}$$

Yield Strength of Steel and Partial Safety Factors

For H36 Steel, $fy := 355\dfrac{N}{mm^2}$

$\gamma := 1.54$

$\phi := 1.11$

Bottom Plate Thickness(t_2)

$$t_2 := 0.73 \cdot s \cdot \left(\frac{k_2 \cdot \gamma \cdot p}{\phi fy}\right)^{\frac{1}{2}}$$

$$\boxed{t_2 = 11.46\,mm}$$

3.2.1.3 Calculation of t_3

$t_3 = cs(Smfy / E)^{1/2}(mm)$

Variables

For H36 Steel, $Sm := 0.908$ and $fy := 355\dfrac{N}{mm^2}$

$E := 20.6 \cdot 10^6 \cdot \dfrac{N}{cm^2}$

For H36 Steel, material conversion factor$Q := 0.72$

Note: Minimum value for c is $0.4*Q^{0.5}$: $c := 0.4 \cdot Q^{0.5}$

$c := 0.339$

Bottom Plate Thickness(t_3)

$$t_3 := c \cdot s \cdot \left(\frac{Sm \cdot fy}{E}\right)^{\frac{1}{2}}$$

$$\boxed{t_3 = 13.41\,mm}$$

3.2.2 Bottom Longitudinal Section Modulus

The LRFD Design formula for Bottom Longitudinal Section Modulus is given by Mansour (2002) as:

$$SM \geq \frac{\gamma \cdot M}{\phi \cdot fy}$$

Variables

$$c := 1.0$$

$$p := 12.611 \frac{N}{cm^2}$$

$$s := 1000mm$$

$$l := 2.5m$$

$$k := 12$$

Bending Moment

$$M := \left(\frac{1000 \cdot c \cdot p \cdot s \cdot l^2}{k} \right)$$

$$\boxed{M = 6.568 \times 10^6 N \cdot cm}$$

Yield Strength of Steel and Partial Safety Factors

For H36 Steel, $fy := 35500 \frac{N}{cm^2}$

$$\gamma := 2.15$$

$$\phi := 1.08$$

Longitudinal Section Modulus

$$SM := \left[\frac{\gamma \cdot M}{(\phi \cdot fy)} \right]$$

$$\boxed{SM = 368.328\,cm^3}$$

This result will be compared to the ABS result in the summary of calculations section of this chapter.

3.2.3 Hull Section Modulus

In developing reliability methods for the calculation of the Hull Section Modulus of bulk carriers, Mansour (2002) makes a calibration point between the ABS rules and the new probability based method, simply put, that the section moduli for both methods are equal for certain ratios of the wave-induced bending moment, and the still-water bending moment, meaning that they both provide the same reliability:

$$SM_{ABS} = SM_{LRFD} \text{ , when } r = \frac{M_w}{M_s}$$

SM_{ABS} *has* already been calculated, so SM_{LRFD} will now be determined using the formulation originally developed for tankers by Mansour et al. (2001):

$$SM \geq \frac{\gamma_1 M_s + \gamma_2 M_w}{\phi f_y}$$

Considering Ship D from Table A-1-1, the greater still-water bending moment occurs in the hogging state, which means that the hogging condition will provide the greater total bending moment for this problem. Following the calibration point at r =1.67 presented by Mansour (2002), the partial safety factors are calculated for the specific Mw to Ms ratio associated with this problem. If this problem specific r value does not exactly match the highlighted values on the calibration point table provided in Appendix 6, then the partial safety factors are found by linear interpretation between the nearest r values.

Applying these to the LRFD formula for Hull Section Modulus, with a H36 grade steel will produce a value for comparison with the earlier calculation using ABS methods.

3.2.3.1. Calculation of the LRFD Hull Section Modulus

Still water Bending Moments,sagging (s) & hogging (h)

$Msws := -202000 \cdot 10^3 N \cdot m$

$Mswh := 367000 \cdot 10^3 \cdot N \cdot m$

Wave Induced Bending Moments, sagging (s) and hogging (h)

$Mws := -5.298 \cdot 10^8 \cdot N \cdot m$ (From earlier ABS Calculations)

$Mwh := 4.864 \cdot 10^8 \cdot N \cdot m$ (From earlier ABS calculations)

Total Vertical Bending Moments, Sagging (s) & Hogging (h)

$Mts := Msws + Mws$ $\quad$ $Mts := -7.318 \cdot 10^8 N \cdot m$

$Mth := Mswh + Mwh$ $\quad$ $Mth := 8.534 \cdot 10^8 N \cdot m$

$Mt := Mth$

Ratio of Mw to Ms (r) for greater Total Vertical Bending Momen

Hogging: $r := 1.325$

As can be seen in Table A-6-1, the nearest r values are 1.2 and 1.4 (on the r=1.67 calibration point table), so a linear interpretation was performed to approximate the best partial safety factors for the problem specific value of r=1.325, which was calculated above.

Partial Safety Factors for hogging state

$r := 1.325$ (See Appendix 6 for explanation)

$\gamma_1 := 0.806$

$\gamma_2 := 1.661$

$\phi := 1.004$

Yield Strength of Grade H36 Steel

$$fy := 355 \frac{N}{mm^2}$$

Design Hull Section Modulus: hogging (h)

$$SMh := \frac{\gamma_1 \cdot Mswh + \gamma_2 \cdot Mwh}{(\phi \cdot fy)}$$

$$\boxed{SMh = 3.097 \times 10^4 \, cm^2 m}$$

This value for the Hull section modulus will be compared to the Hull Section Modulus calculated using the traditional ABS methods in the next section.

3.3 Summary of Calculations

The procedures demonstrated above were applied to four sample bulk carriers, the data for which was provided by Wang (2000). Bulk Carrier BC21 was used primarily for the calculation and comparison of the Bottom Plate Thicknesses. Carriers D, E, & F were then used for the longitudinal section modulus calculation and comparison as well as the Hull Section Modulus calculation and comparison. Using both design approaches, the data was reduced and presented in graphical format in Appendix 4 (Bottom Plate Thickness), Appendix 5 (Bottom Longitudinal Section Modulus), and Appendix 6 (Hull Section Modulus). The following subsections summarize the data from the sample calculations performed so far in the text, so that evaluations and observations can be presented in the next chapter.

3.3.1 Bottom Plate Thickness

Figure 3.1 illustrates the comparison of the calculation of Bottom Plate Thickness, from the earlier example. From the diagram, it can be seen that for the Load Case A condition, the ABS and the LRFD results match very closely for this particular vessel, within 0.05 mm, which is well within tolerance.

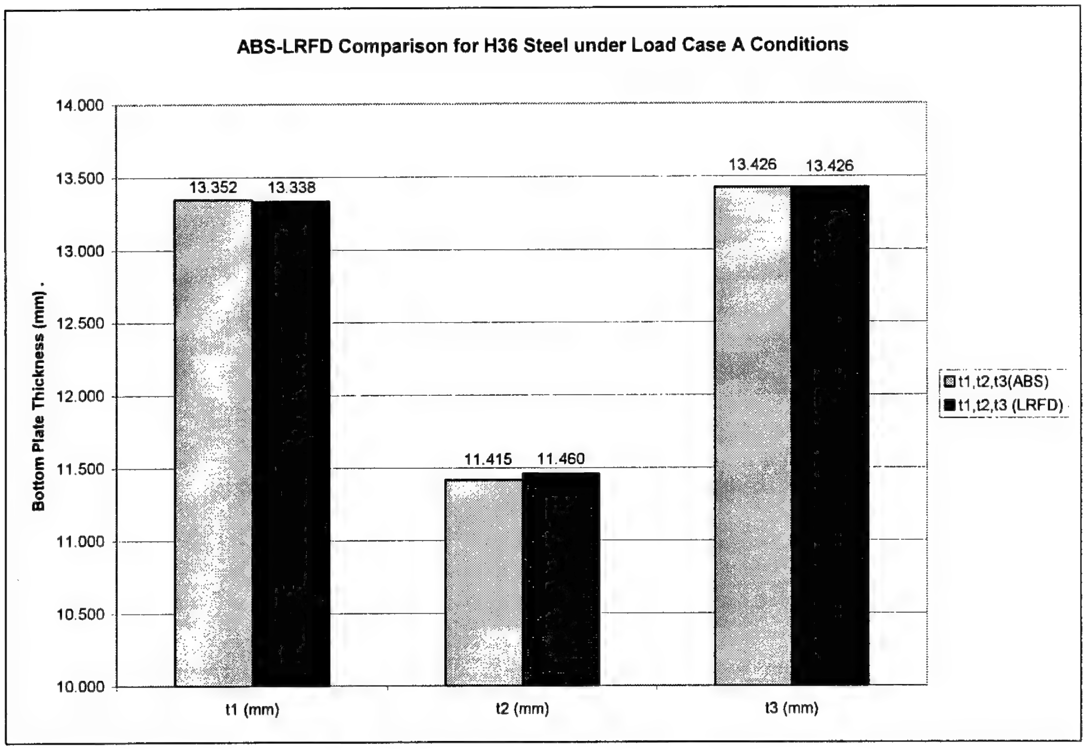


Figure 3.1. ABS / LRFD Bottom Plate Thickness

It is worth noting at this point that the governing Bottom Plate Thickness for the calculated example is t_3, which means that this will be the thickness used in design. Depending of whether this trend continues in later examples, the development of partial safety factors for this part of the calculation will be crucial to the success of LRFD in this small part of the overall ship design. Since no partial safety factors have been developed to support LRFD specific design calculations of t_3 to date, this would mean that the

thickness used in the design of bottom plating would be the same regardless of whether ABS rules or LRFD rules are used, in situations where t_3 is found to be the governing thickness. This will be discussed further in the evaluation section of the paper, based on review of the findings in appendix 4.

Appendix 4 shows the reduction of the data in graphical comparison of the ABS Rules and the LRFD reliability approaches for a number of variations applied to the sample ship BC21, provided by ABS. The variations include steel strength, longitudinal spacing, and finally, both Load Case A and Load Case B are considered separately for their respective nominal pressures. The only variable that is not changed for these analyses is the draft, since the pressures provided by ABS in Appendix 2 are based on this draft, and these same pressures are used for all calculations for consistency in comparison. The results of these comparisons will be discussed later in the evaluation section.

3.3.2 Bottom Longitudinal Section Modulus

Figure 3.2 shows a comparison of the ABS and LRFD Bottom Longitudinal Section Modulus results for a length of 2.5 meters and a spacing of 1.0 meter for the typical four grades of steel, with the use of effective struts included. This representation includes the previously calculated example, which was determined using H36 grade steel for Load Case A with nominal pressure (|pi-pe|) taken from the ABS Provided pressure data shown in Appendix 2. Further comparisons for varying lengths, spacings and inclusion or exclusion of effective struts are shown in Appendix 5. All of these comparisons will be discussed in the evaluation part of Chapter Four.

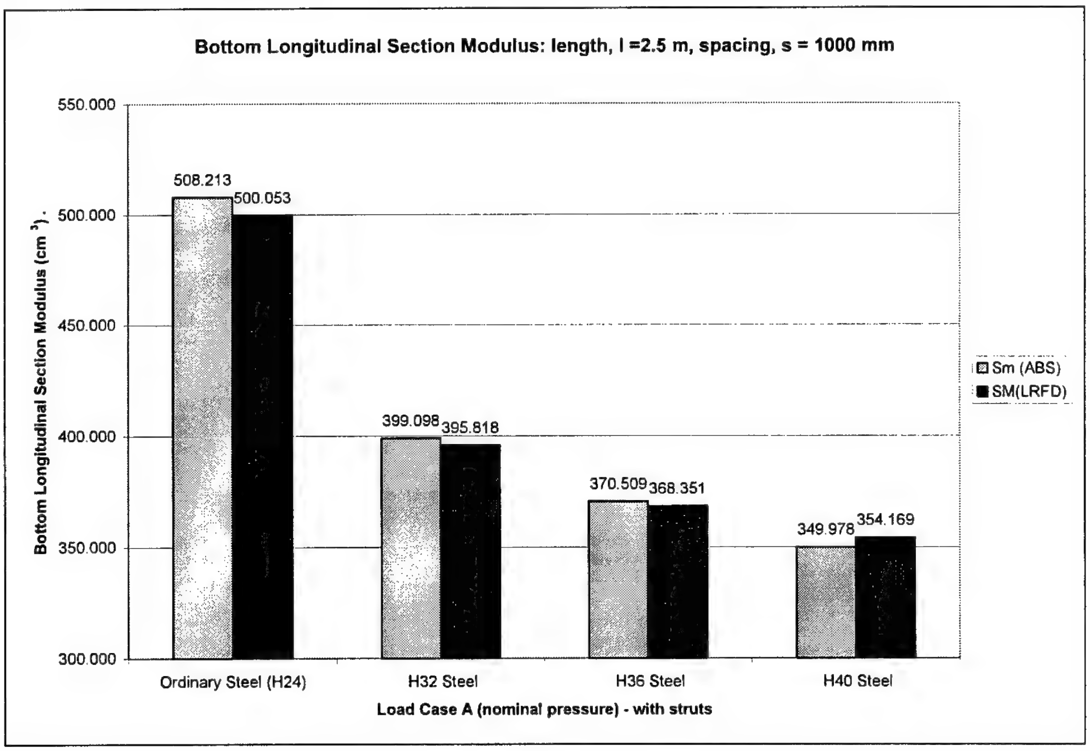
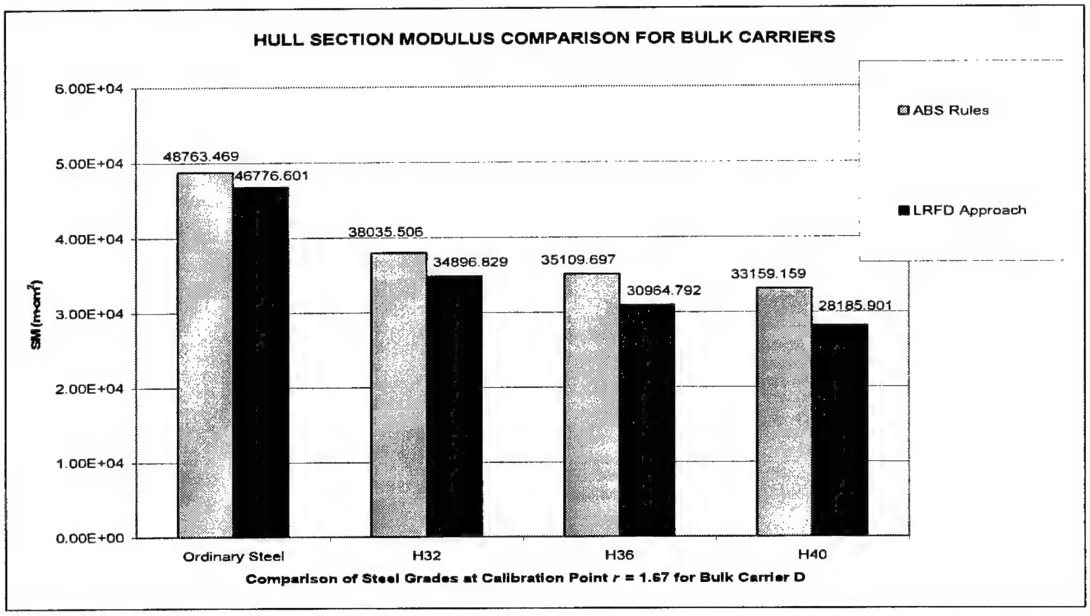


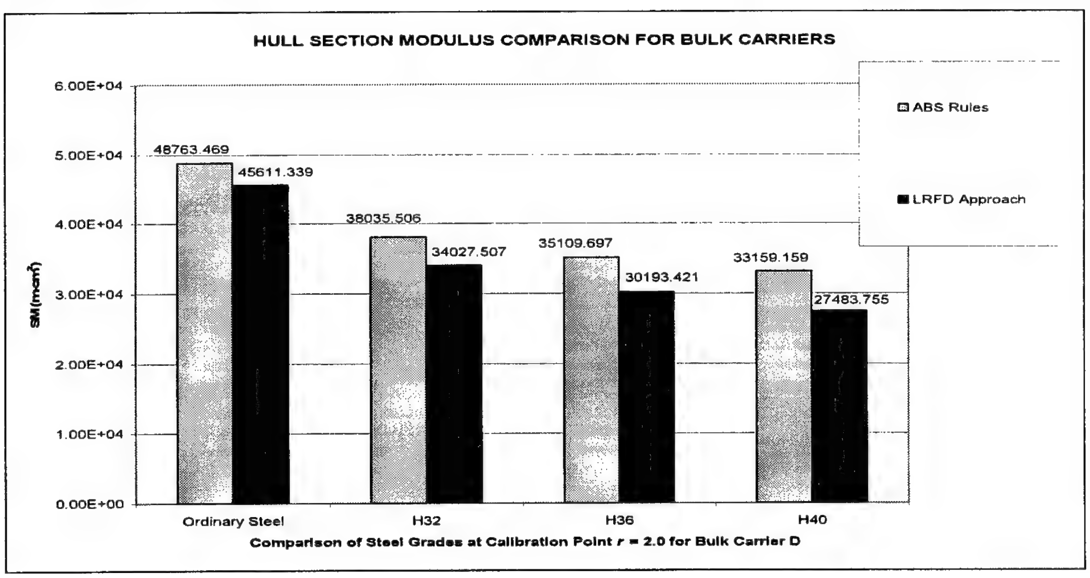
Fig. 3.2. ABS/LRFD Bottom Longitudinal Section Modulus with struts

3.3.3 Hull Section Modulus

Figure 3.3 shows a graphical comparison of these calculations for each of the three sample bulk carriers provided by ABS. See Appendix 6 for further comparisons.



a) LRFD Values based on partial safety factors taken from Mansour (2002) Calibration Point of r=1.67



b) LRFD Values based on partial safety factors taken from Mansour (2002) Calibration Point of r=2.0

Figure 3.3. ABS/LRFD Bulk Carrier D Hull Section Modulus for all Grades of Steel

Chapter 4

Evaluations & Conclusions

4.1 Evaluations

Overall, the comparisons performed in this paper are showing that the use of LRFD design methods is closely comparable and sometimes better to varying degrees than the more traditional ABS methods. It can be said that they are better because the LRFD design approach has been calibrated in its partial safety factors to provide the same reliability as the ABS design methods. This means that the elements of the ship that are being compared will have the same probability of failure (Pf) whether the LRFD method or the ABS method is used. It is therefore reasonable to say that wherever a member size or section modulus is smaller for the LRFD calculation than from using the ABS guidelines, then the size of that element can be reduced safely, without compromising the expected probability of failure or reliability associated with its design. The following sections will do into more detail about the specific comparisons made between the ABS and LRFD methods for the Bottom Plate Thickness, the Bottom Longitudinal Section Modulus and the Hull Section Modulus.

4.1.1 Bottom Plate Thickness

After studying all the comparisons for Bottom Plate Thickness presented in Appendix 4, it seems that in general, the ABS and LRFD methods provide very similar

results (within 0.05 mm for the most part) when comparing for Load Case A. It was found that the dominant thickness for design was t_1 for most situations, whether Load Case A or Load Case B was being examined. However, one concern arose for the higher grades of steel associated with Load Case A. It was found that the dominant thickness was t_3 in these situations, which is not the best result, since no partial safety factors have been developed for t_3 to date. This means that when t_3 is used as the design thickness, there is no real LRFD method developed yet, so it basically designed using the ABS guidelines.

While examining the comparison results for Load Case B, it was found that the ABS and LRFD methods matched for t_2, but that for t_1, a slight size reduction could be achieved by using the LRFD design approach of almost a millimeter in some cases. This might seem insignificant, but when the big picture is considered, reduction of a millimeter over the entire bottom surface of a bulk carrier could mean quite a saving in manufacturing costs for a ship builder. Although this seems promising, a great deal more experimental research and testing should be done to make absolutely sure that the slight reduction in thickness will provide the same reliability as the tried and tested ABS design methods.

4.1.2 Bottom Longitudinal Section Modulus

The comparison of the Section Modulus of the Bottom Longitudinal Members was performed for a number of sizes (lengths) and member spacings, and it was found that the comparison between the LRFD method and the ABS method was similar for all studies. The magnitudes of the section modulus was different for each case, but they all

seemed reasonably comparable to ABS, with the LRFD arriving at a slightly lower section modulus, in the range of about 2 cm^3 to 20 cm^3 less than the corresponding ABS Section modulus for the varying steel strengths, member lengths and member spacing.

The only real concern found in the comparison was for the high strength steel of grade H40. In every configuration for this grade of steel, the ABS results was smaller than the LRFD results by a range of approximately 2 cm^3 to 20 cm^3. This seemed to be a strange result, so the calculations were rechecked, and they seemed to be in order. The two possible solutions are that they is some flaw in the calculation that was overlooked, or the calibration of the partial safety factors does not work in the favor of LRFD for the case of H40 grade steel used for Bottom Longitudinal Design. It is definitely worth further investigation, and one would hope that it is merely a flaw in the calculation method, as this is easier to fix that to recalibrate the LRFD partial safety factors to bring the Section Modulus in line with or slightly better than the ABS results. All in all, the H40 Grade Steel results are still close to the ABS result, although a little higher, so they could still be used, but they would be just slightly conservative compared to the ABS calculated Section Modulus of the Bottom Longitudinal Members.

4.1.3 Hull Section Modulus

Two main approaches were taken to compare the LRFD and the ABS design methods for the calculation of the Hull Section Modulus. The first approach was to compare the results of using all four steel grades for each individual sample bulk carrier (D, E & F from Table A-1-1), and the second approach was to consider each steel grade and compare all three bulk carriers for that specific grade of steel.

These comparisons were made for the two calibration points recommended by Mansour (2002), both at r = 1.67 and at r = 2.0, where r is the ration of Wave Bending Moment to Still Water Bending Moment. It was found that in general the results obtained for the r = 2.0 comparison were less than those for r = 1.67, which was expected since the two points have different associated reliabilities. The r = 1.67 has a reliability safety index of β = 4.5, which reduces to a probability of failure of: Pf =2.210E-5, whereas, the r =2.0 has a reliability index of β =4.35, which reduces to a probability of failure of, Pf =3.35E-5. This basically means that the r = 2.0 point is more likely to fail than the r =1.67 point, which makes sense, as it produces a Hull Section Modulus that is smaller. Another way of looking at this is that the Hull Section Modulus for r = 1.67 is bigger in magnitude and therefore more conservative, and less likely to fail than the Modulus generated using the r = 2.0 criteria.

The comparison of the different steels for each individual bulk carrier showed that the LRFD method resulted in size reduction for all situations. Furthermore, it was found that the for each ship, the stronger the steel used for design, the greater the reduction in LRFD Hull Section Modulus compared to ABS Hull Section Modulus.

When the four grades of steel were considered separately for all three ships, it was again found that the LRFD method produced lower Hull Section Modulus values in all cases, and comparing the three carriers for each steel, it was seen that as the size of the ship increased, the reduction in LRFD Hull Section Modulus compared to the ABS result also increased. The order of magnitude of reductions for both ship and steel grade comparison ranged from approximately 1887 m-cm^2 to 51340 m-cm^2, which could mean great savings in the future of ship building without a compromise in the safety criteria

built into the design, once LRFD is embraced as the exclusive way forward for ship design.

4.1.4 Partial Safety Factor for Capacity/Strength, φ

Intuitively, this author understands that with LRFD rules, the resistance factor, φ, is typically less than unity. In many cases throughout this paper the factor has been greater than unity, for example, 1.04. This happens because the calibration between the LRFD and ABS methods was conducted at the normalized mean value of the load and strength. Since the normalizing process called for dividing the strength , fy, by 1.2, then the partial safety factors developed for the normalized fy (which were less than unity), had to be multiplied by 1.2 in order to use them with fy under normal circumstances. Although this produces valid results, the author feels that it might be better to include the 1.2 multiplier in the LRFD formula so that the original nominal partial safety factor, which is less than unity, as mentioned before, could be used, thus providing engineers familiar with other LRFD procedures with the expected type of factor.

This could be done in two transitional steps (bottom plate thickness is used to demonstrate this idea). First, change the constant in the thickness formula for LRFD to 0.73/1.2. By writing it this way, people who are used to ABS will understand that it is the usual formula divided by 1.2. Once this is established, the second step involves the constant for the LRFD formula being changed in the literature to 0.61, which is the result of 0.73/1.2. This way, the resistance factor can be represented as less than unity. This ties the methodology back to the standard LRFD thinking.

4.2 Conclusions

This paper has been written based on the assumption that the LRFD partial safety factors being used have been correctly calibrated to provide the same level of safety as was integral to the ABS design method. The confirmation of that assumption is beyond the scope of this paper, but it can be accepted with a high degree of confidence due to both the amount of high quality work that went into developing the factors, and the fact that these factors have been presented to the naval architecture international community for review and discussion. If any corrections are made to the factors in the future, based on this peer review, they will probably be minor in nature. Based on this acceptance of the assumption outlined above, the following conclusions can be drawn from the findings of this paper.

After performing all the various comparisons and evaluations for each of the three elements addressed in this paper, namely, the Bottom Plate Thickness, the Bottom Longitudinal Section Modulus, and the Hull Section Modulus, it seems reasonable to state that the LRFD approach produces similar or better results than the traditional ABS design method, in almost every situation. In the few areas where the LRFD result was a little bigger, it is still close enough to the corresponding ABS result to be considered a similar result.

The idea of changing ship design from ABS guidelines to a new LRFD reliability based design approach is attempt to change a "design culture" that has been present for many years. Changing any type of culture is a daunting task, and this is no different. This paper has shown that for three elements of the design process, the LRFD is as good

as or slightly better than the ABS methods, but this effort is only a small piece of the big picture. In order to convince all the naval architects who have sworn their livelihoods on the ABS rules, no element must be neglected. Further research of a similar nature to this paper must be performed for each and every element of the design process. Only after the LRFD approach has been shown to be equal or better than the ABS guidelines for each and every aspect of the ship design process, will there be a chance to convince many naval architects to make the transition. That transition will take many more years, but ultimately, the end will justify the means, as the savings made in shipbuilding by LRFD methods can provide the shipbuilders with the revenue to either work on new developments or construct extra ships.

4.3 Marine LRFD Software Development

One of the most important steps in any new process is the development of software, which is user friendly and will perform without problems saving the designer's time, so that he/she can address more pressing issues associated with the design process.

There are many software platforms available for development of such software. The author feels that the best platform will ultimately be MATLAB, which is very powerful and capable of managing the calculation of all design elements for a ship. There will also be other proprietary software written on various platforms in different computer languages, but for the transition, MATLAB seems to be the most globally used platform for dissemination for new LRFD design methods.

For this paper, MathCAD and Microsoft Excel were used together. MathCAD was used to develop the calculations, and then Excel was used to do all the comparison. This

approach worked well, as the calculations could easily be checked in MathCAD, and the results compared to those found on the Excel Spread Sheet. Excel is good for viewing a number of different calculation results on a single page, but has a drawback in that the formulae in each cell mostly refer to other cells, and does not let the reader immediately see what is being calculated, which is why it is worth while using it in conjunction with MathCAD for the initial software development process.

The advantage of future development of a MATLAB version of this type of LRFD calculation software is that the calculations are buried in the program and the user can easily and quickly change the variables as they are usually defined at the start of the program. With even a limited understanding of MATLAB, the user will be able to produce valuable data for all necessary design criteria.

4.4 Final Comments

This research has been a rewarding experience and an opportunity to make a small contribution to the enormous task of developing justification for a move towards the use of LRFD reliability approaches in ship design. The author would like to thank Professor Alaa Mansour of the Ocean Engineering Graduate Group at the University of California, Berkeley for the inspiration, support and mentorship that he provided throughout the research effort.

Appendix 1

Sample Data Provided by ABS

Table A-1-1 consists of data for three ships provided by Wang (2002):

Bulk Carrier

Ship	LBP	Lscantling	B	D	Cb	SW(hog)	SW(sag)
D	128.4	127.458	23	11.5	0.794	367000 kN-m	202000 kN-m
E	217	213.594	32.26	19.3	0.836	173000 t-m	151000t-m
F	279	283.6	44.98	24.4	0.8538	4002500 kN-m	2913600 kN-m

Table A-1-1: Sample Bulk Carrier Data

Appendix 2

Additional Data Provided by ABS

BC21 Bulk Carrier

L	211.945	(m)	Speed	14.0	(knots)
B	32.200	(m)	Cb	0.8654	
D	18.600	(m)			
d	13.430	(m)			

XP	Distance from centerline
YP	Distance from baseline
Pia	Internal Tank Pressure, Load Case "a" in 5-3-3/Table 3
Pea	External Pressure, Load Case "a" in 5-3-3/Table 3
Pib	Internal Tank Pressure, Load Case "b" in 5-3-3/Table 3
Peb	External Pressure, Load Case "b" in 5-3-3/Table 3

Design Pressure for Local Longitudinals

MEMR		XP m	YP m	Pia kgf/cm2	Pea kgf/cm2	Pib kgf/cm2	Peb kgf/cm2	P kgf/cm2
KPL-	1	0.810	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	1	1.620	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	1	2.430	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	2	4.050	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	3	4.860	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	3	5.670	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	3	6.480	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	4	8.100	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	5	8.910	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	5	9.720	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	5	10.530	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	7	12.150	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	7	12.960	0.000	1.997	0.711	0.000	1.833	1.833
BTM-	7	13.770	0.000	1.997	0.711	0.000	1.833	1.833
SHL-	1	16.100	1.700	1.667	0.502	0.000	1.735	1.735
SHL-	2	16.100	2.550	1.561	0.372	0.000	1.706	1.706
SHL-	2	16.100	3.400	1.453	0.243	0.000	1.676	1.676
SHL-	2	16.100	4.250	1.343	0.113	0.000	1.647	1.647
SHL-	8	16.100	14.900	1.227	0.000	0.000	0.953	1.227
SHL-	8	16.100	15.750	1.107	0.000	0.000	0.734	1.107
SHL-	8	16.100	16.600	0.986	0.000	0.000	0.515	0.986
SHL-	8	16.100	17.450	0.862	0.000	0.000	0.296	0.862

Table A-2-1 BC 21 Bulk Carrier Data

Appendix 3

Steel Properties from ABS Rules

Bulk Carrier - Tensile Properties of Ordinary Strength Hull Structural Steel, 100mm and under - from ABS Table 2/1.1-2 (1996).			Strength Reduction Factor, S_m. from ABS 5-3-4/7.3.1
Grade	Tensile Strength/ N/mm^2	Yield Point minimum/ N/mm^2	
A B D E	400/520	235	1

Table A-3-1: Ordinary Strength Steel Properties

Bulk Carrier - Tensile Properties of Higher-Strength Hull Structural Steel, 100mm and under - from ABS Table 2/1.1-2 (1996).			Strength Reduction Factor, S_m. from ABS 5-3-4/7.3.1
Grade	Tensile Strength/ N/mm^2	Yield Point minimum/ N/mm^2	
AH 32 DH 32 EH 32 FH 32	440/590	315	0.95
AH 36 DH 36 EH 36 FH 36	490/620	355	0.908
AH 40 DH 40 EH 40 FH 40	510/650	390	0.875

Table A-3-2: High Strength Steel Properties

Appendix 4

Bottom Plate Thickness Comparisons

The following pages contain charts which illustrate the ABS/LRFD comparisons for the bottom plate thickness of the BC21 Bulk Carrier. The first set of tables and charts show the Bottom Plate Thickness results for the nominal pressures for both Load Case A and B (ABS 5-3-3 Table 3). The calculations of these data sets followed the format of the examples outlined in the main body of the text.

Figures A-4-1 to A-4-4 are the charts for Load Case A conditions, and Figures A-4-5 to A-4-8 are the charts for Load Case B conditions.

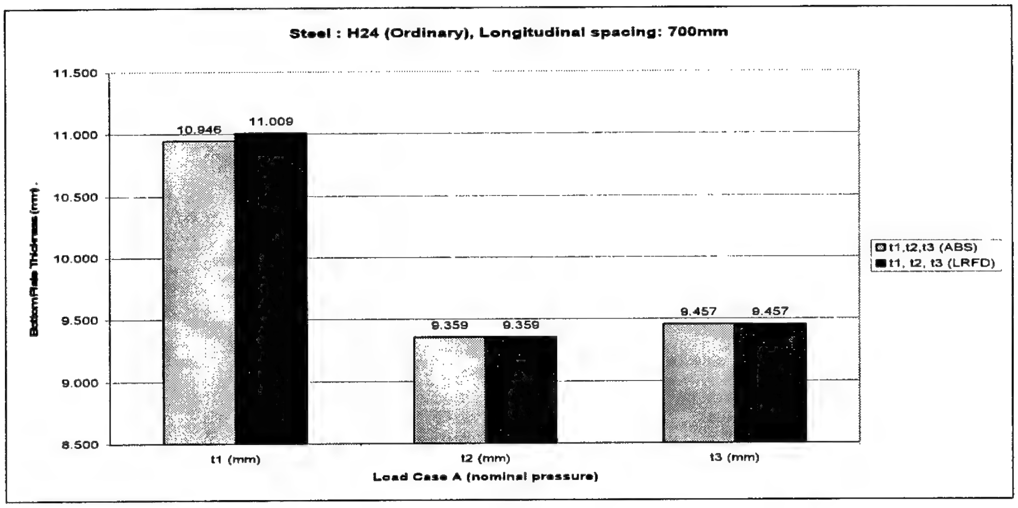
The Partial Safety Factors used to calculate the LRFD Values of Bottom Plate Thicknesses t_1 and t_2 are shown in table A-4-1 and A-4-2 below respectively. These tables come from the paper by Mansour (2002).

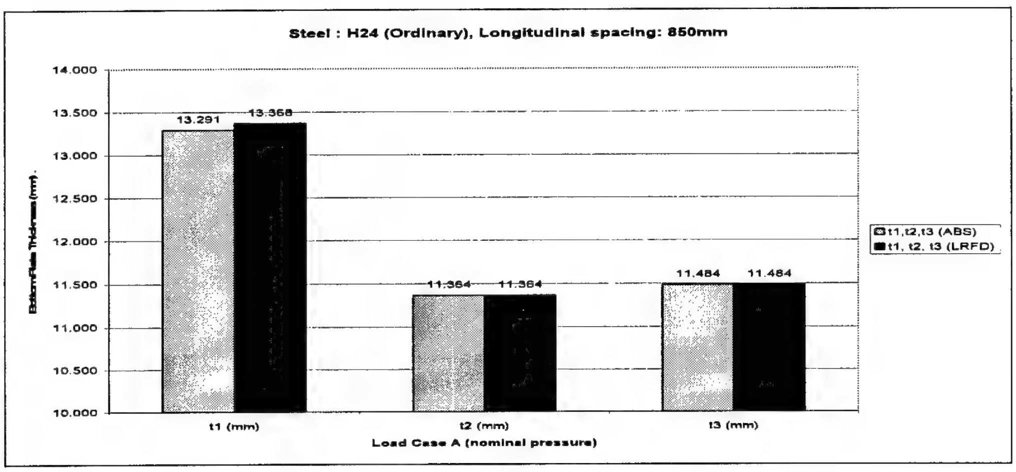
t_1	Ordinary Steel (H24)	H32	H36	H40
φ	1.04	1.04	1.03	1.02
γ	2.63	2.72	2.83	2.95
β	5.20	5.35	5.55	5.75
Pf	9.98E-08	4.41E-08	1.43E-08	4.48E-09

Table A-4-1 Partial Safety Factors for Calculation of t_1 for Bottom Plating

t_2	Ordinary Steel (H24)	H32	H36	H40
φ	1.12	1.12	1.11	1.11
γ	1.40	1.48	1.54	1.59
β	2.25	2.50	2.70	2.85
Pf	1.22E-02	6.21E-03	3.47E-03	2.19E-03

Table A-4-2 Partial Safety Factors for Calculation of t_2 for Bottom Plating





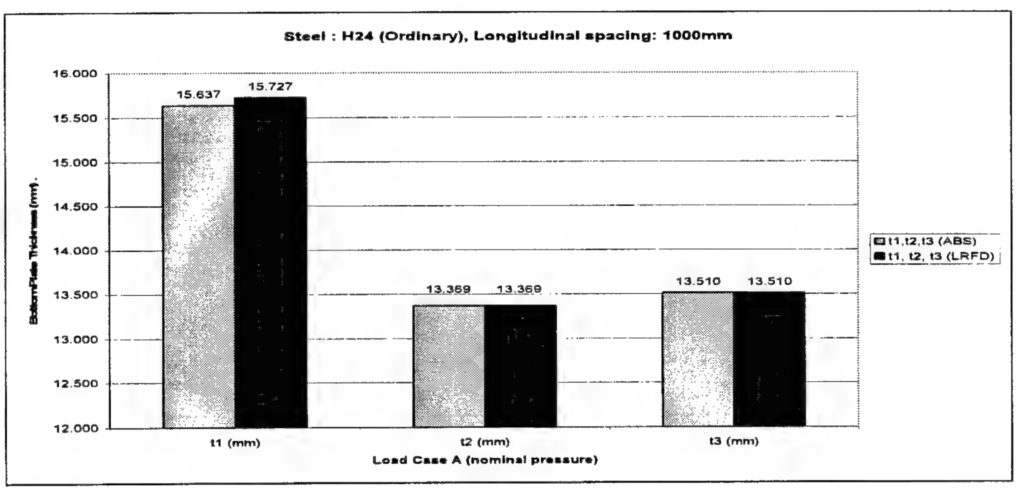
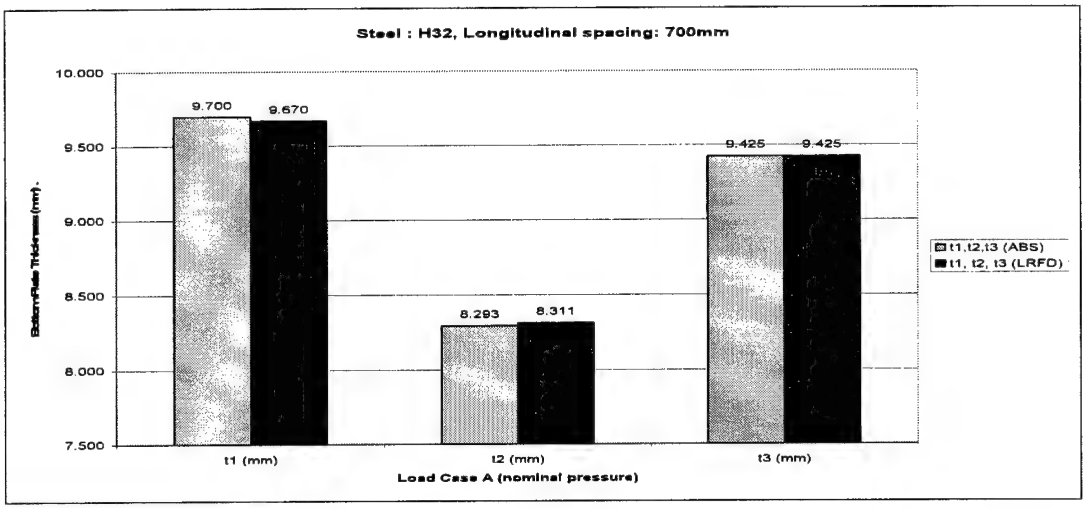
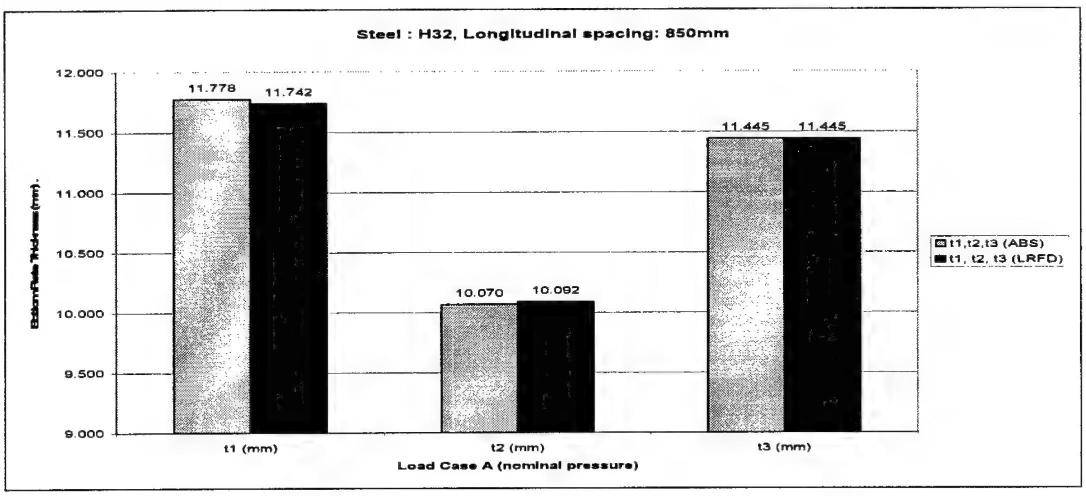


Fig.A-4-1 Bottom Plate Thickness (Load Case A, Ordinary Steel)





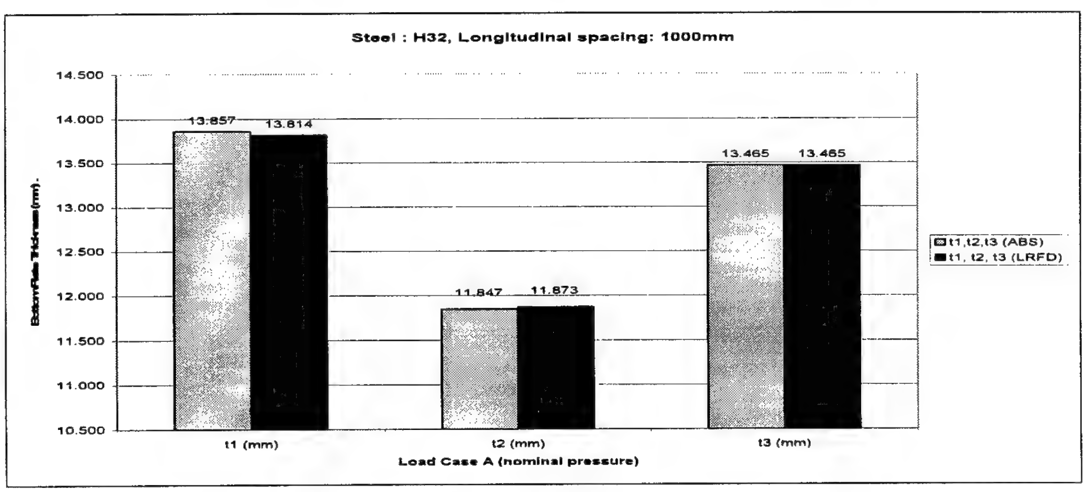
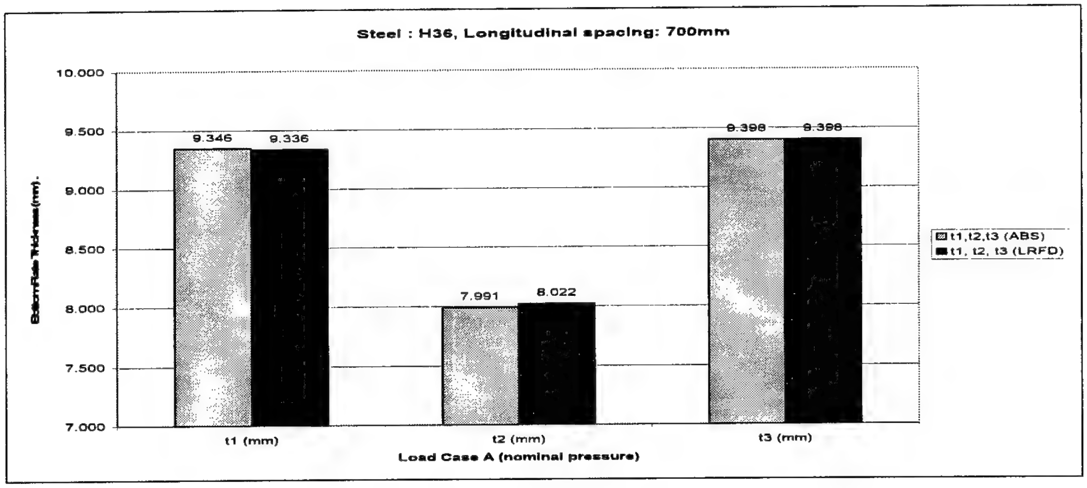
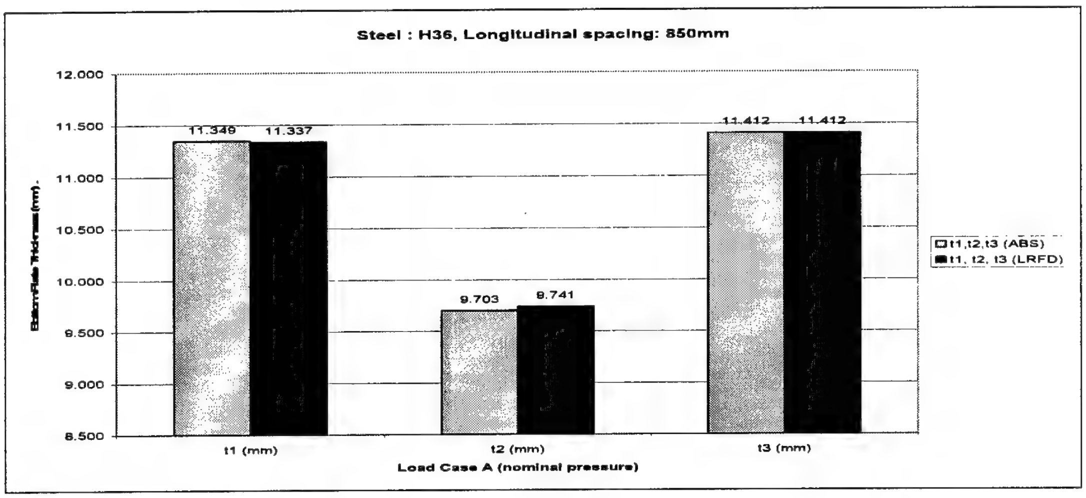


Fig.A-4-2 Bottom Plate Thickness (Load Case A, H32 Steel)





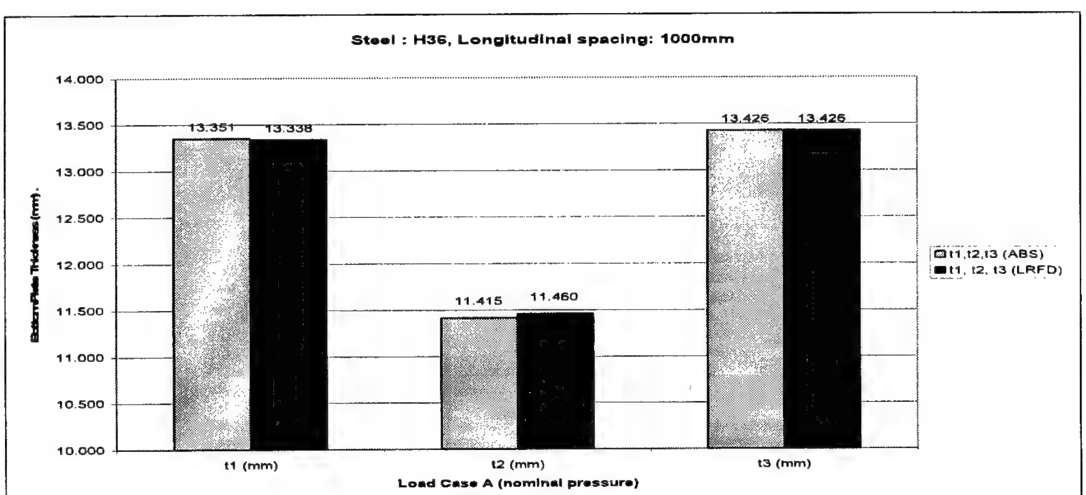
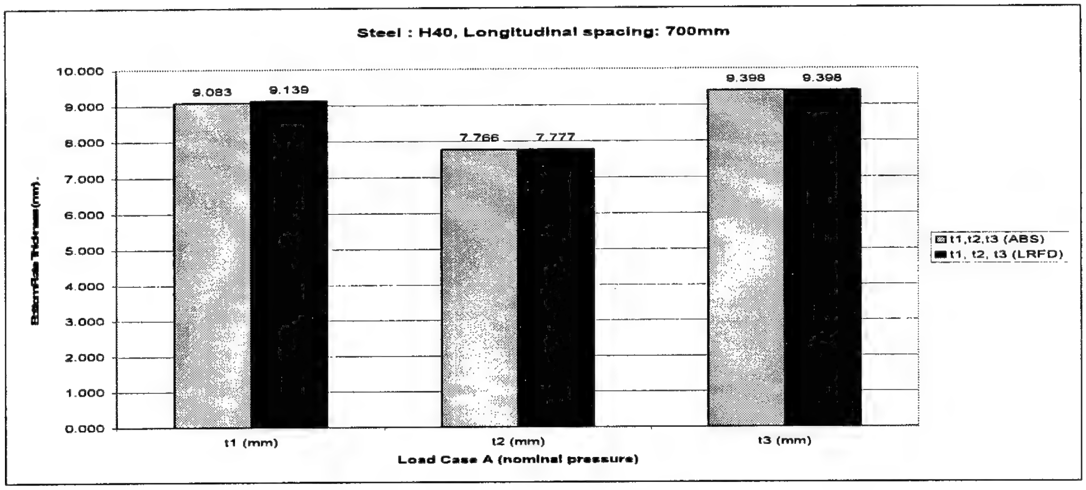
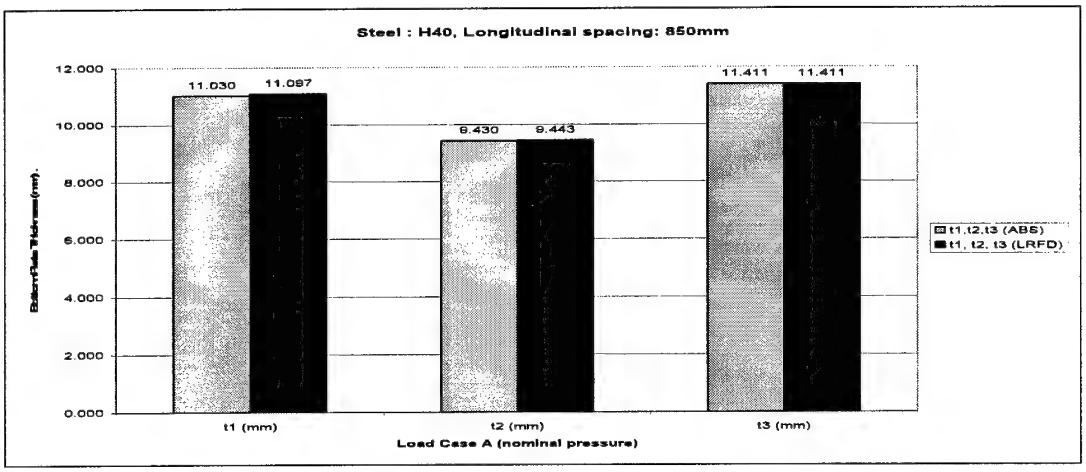


Fig.A-4-3 Bottom Plate Thickness (Load Case A, H36 Steel)





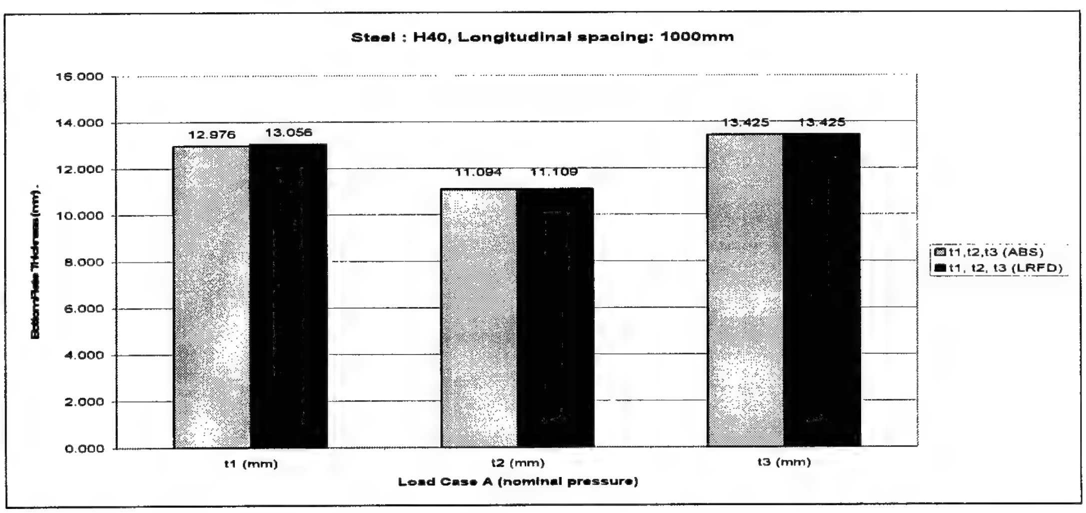
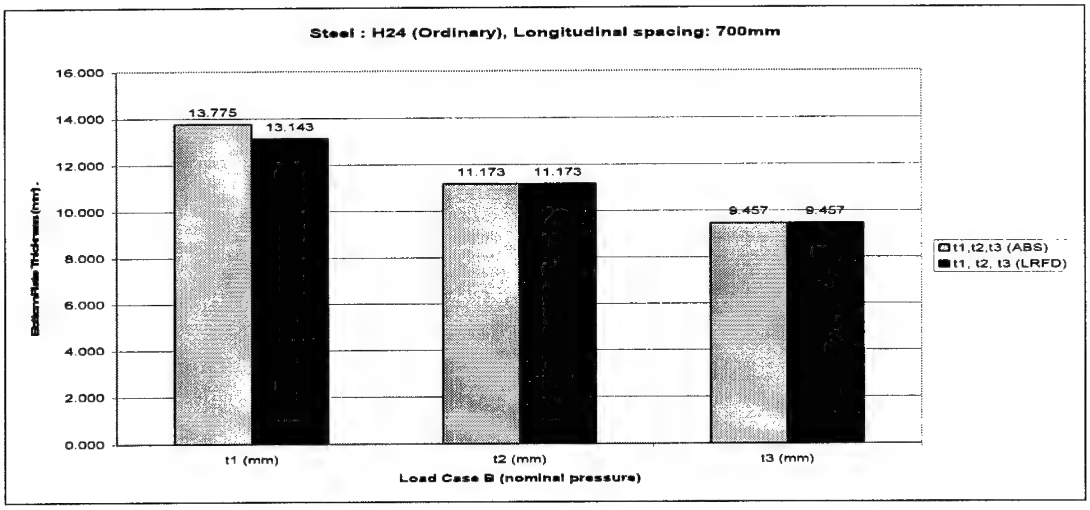
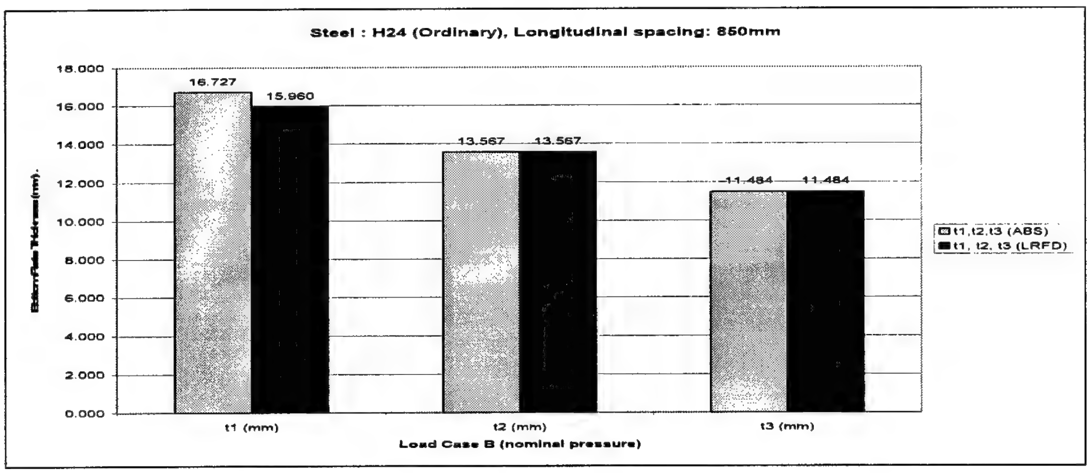


Fig.A-4-4 Bottom Plate Thickness (Load Case A, H40 Steel)





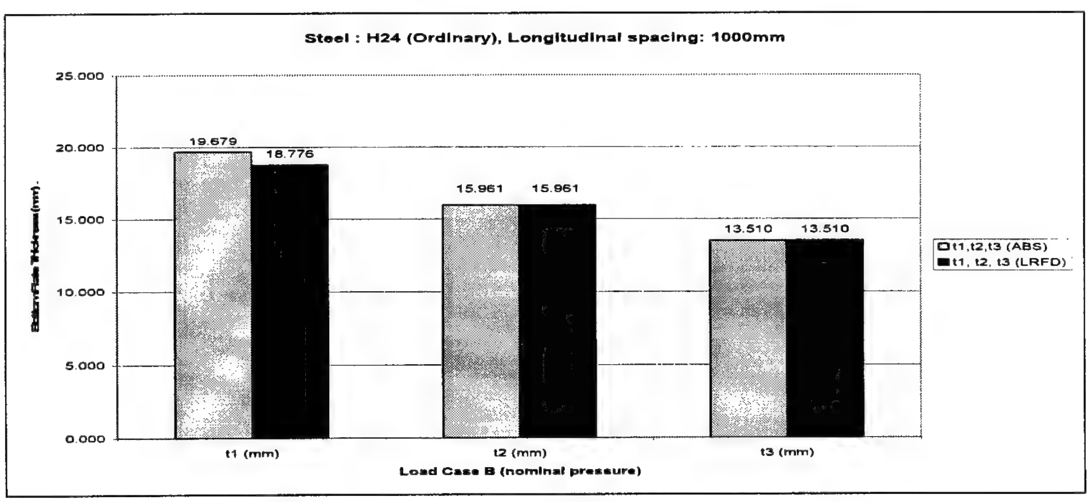
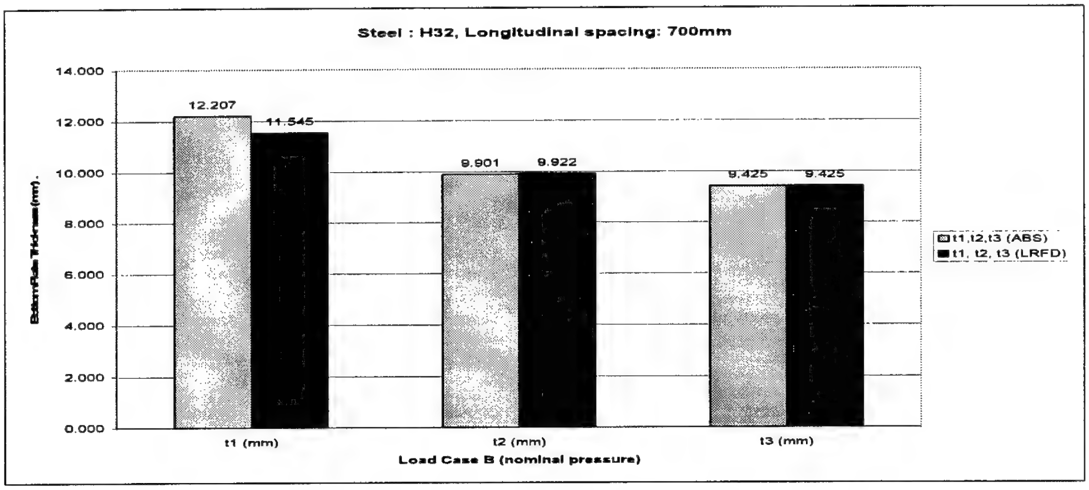
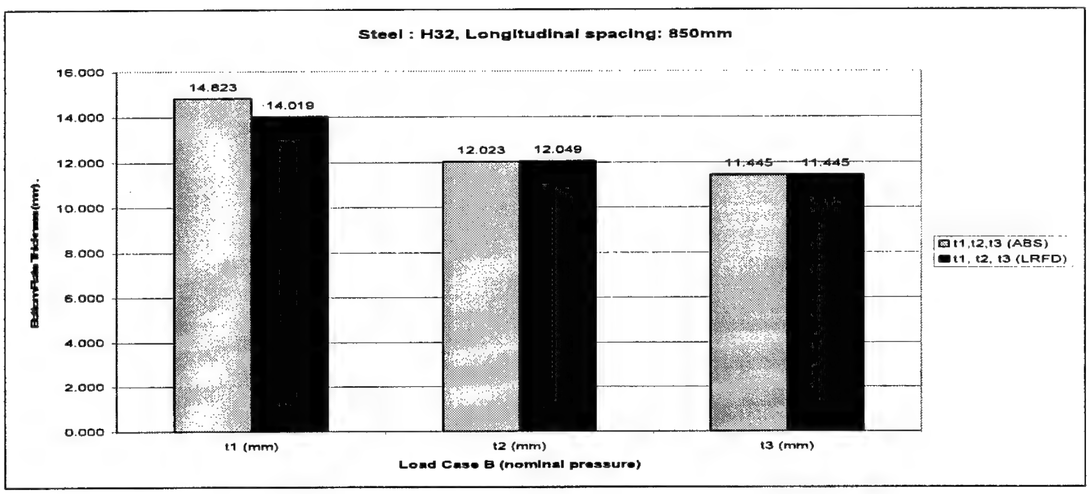


Fig.A-4-5 Bottom Plate Thickness (Load Case B, Ordinary Steel)





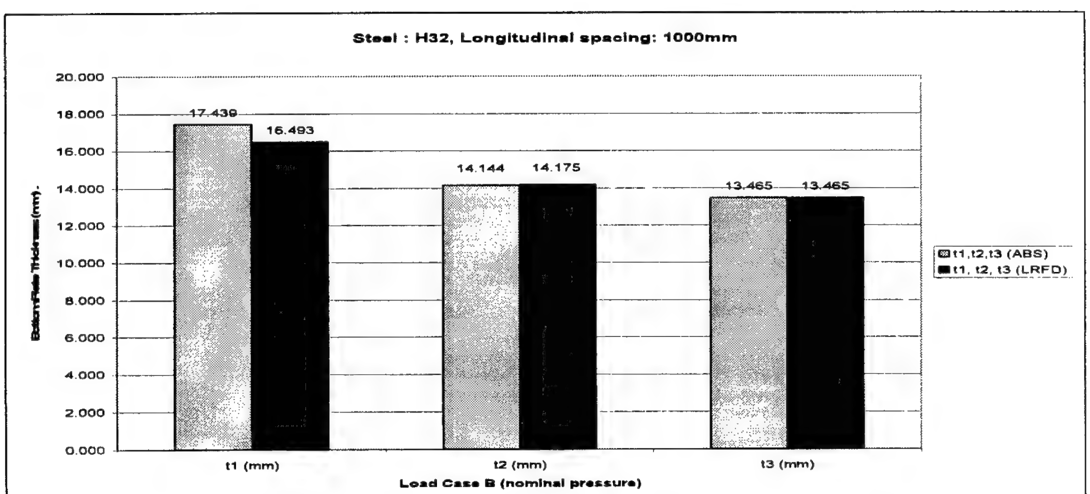
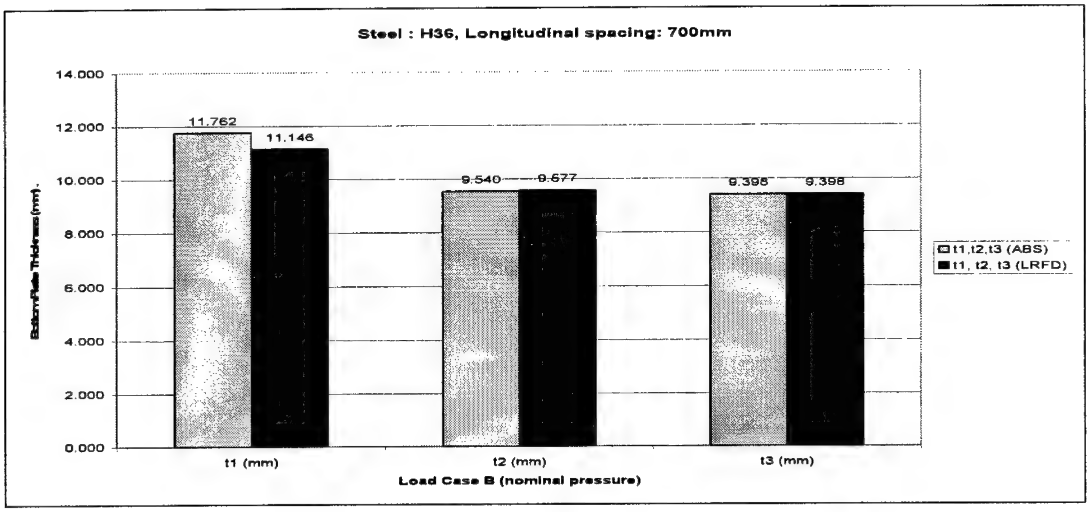
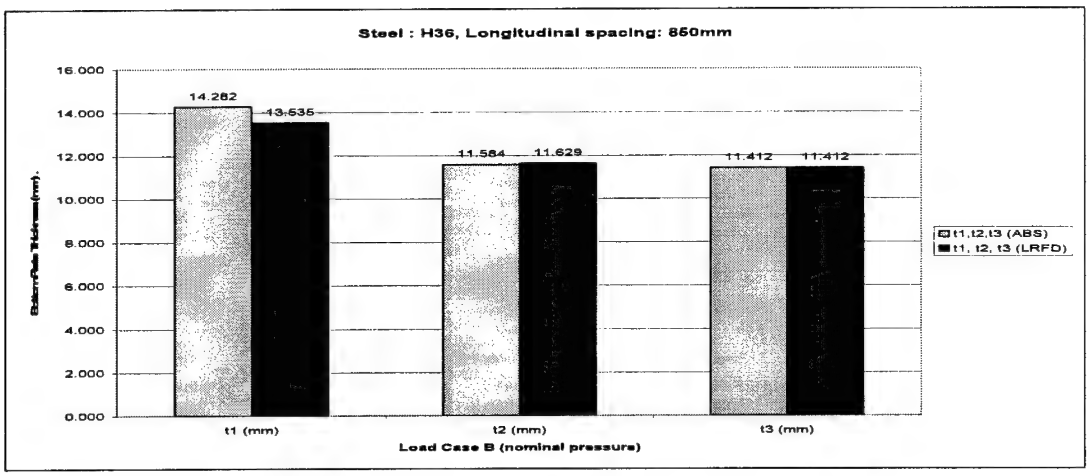


Fig.A-4-6 Bottom Plate Thickness (Load Case B, H32 Steel)





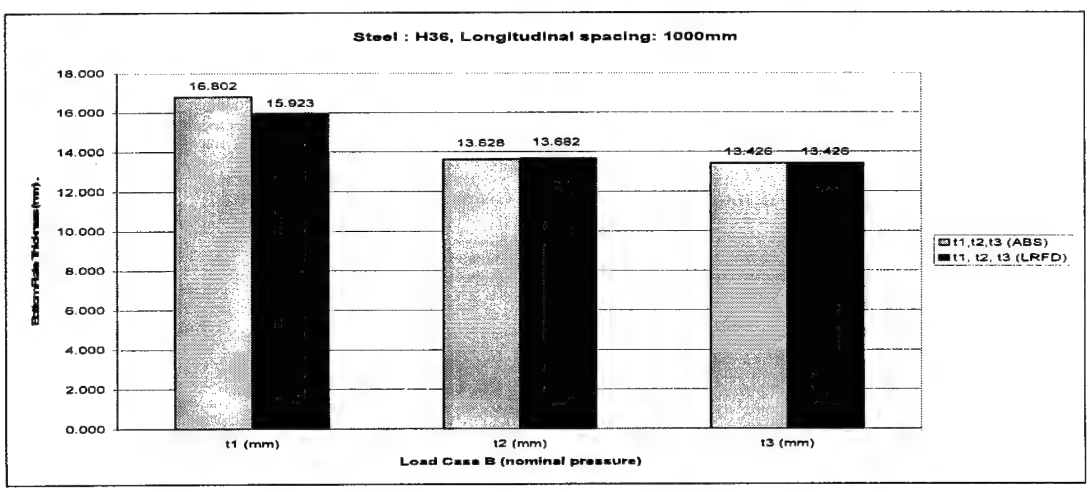
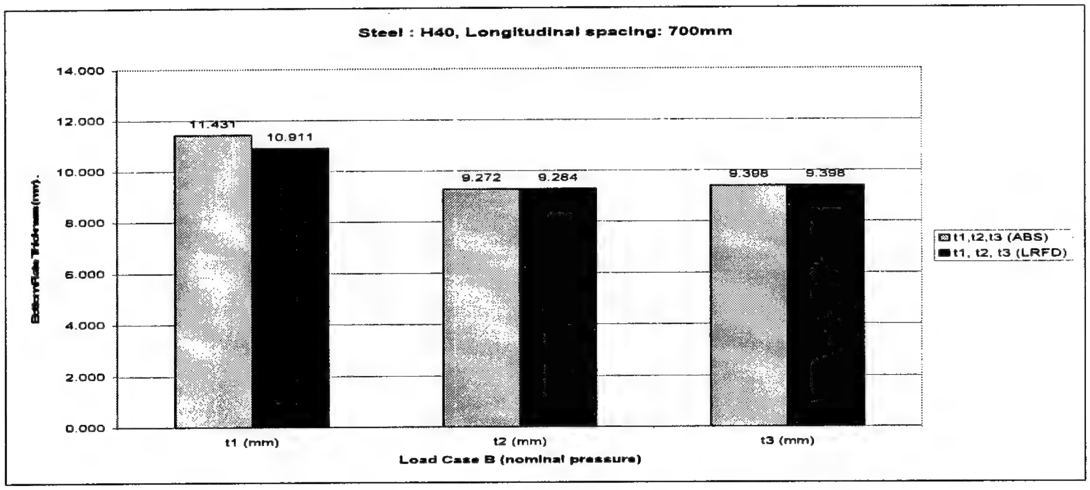
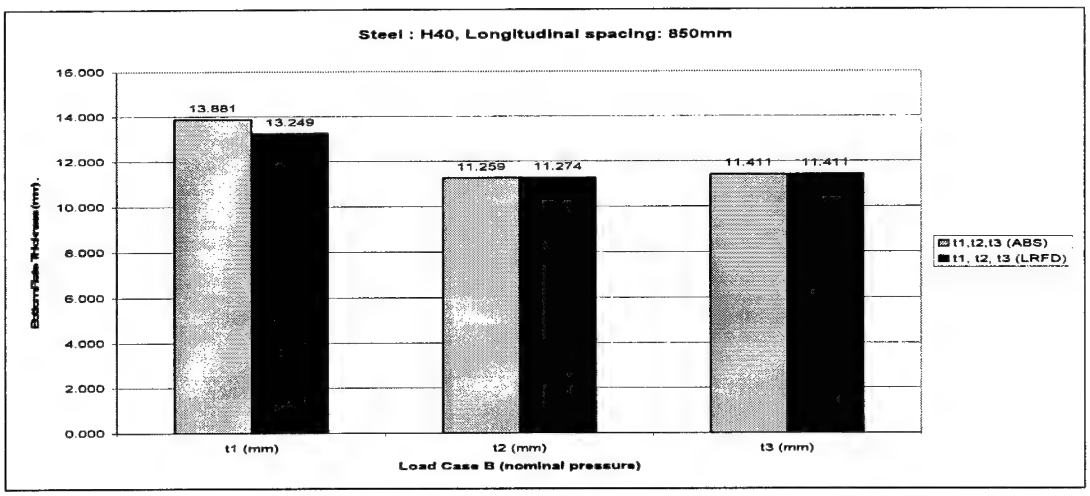


Fig.A-4-7 Bottom Plate Thickness (Load Case B, H36 Steel)





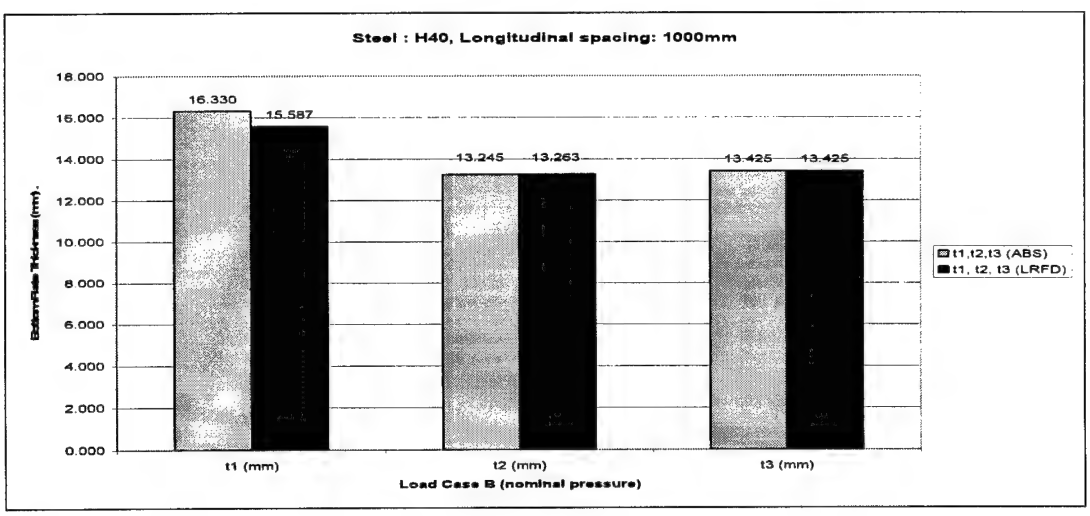


Fig.A-4-8 Bottom Plate Thickness (Load Case B, H40 Steel)

Appendix 5

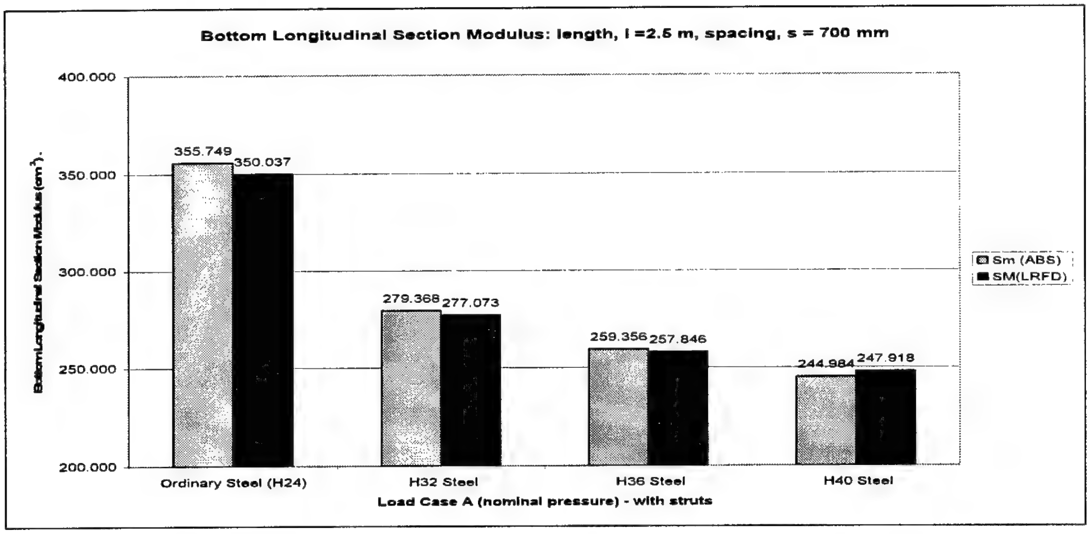
Bottom Longitudinal Section Modulus Comparisons

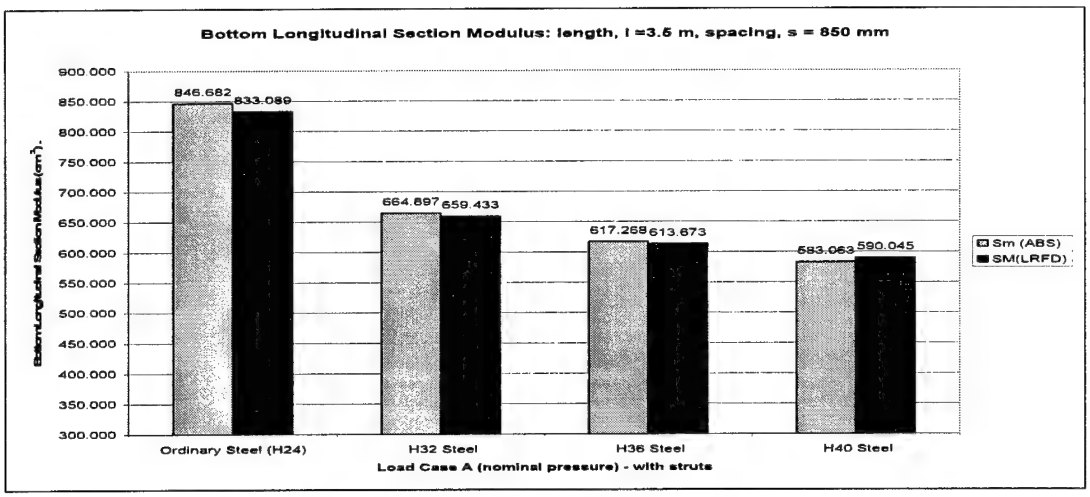
The partial safety factors used in calculation of the LRFD values for the Section Modulus of the Bottom Longitudinals is shown below in table A-5-1. This also shows the reliability index and probability of failure associated with each set of these factors, and their related steel grade.

	Ordinary Steel (H24)	H32	H36	H40
φ	1.09	1.08	1.08	1.07
γ	1.95	2.05	2.15	2.25
β	3.75	4.00	4.20	4.40
Pf	8.84E-05	3.17E-05	1.34E-05	5.42E-05

Table A-5-1 Partial Safety Factors for Bottom Longitudinals form Mansour (2002)

The example shown in the text was for Bottom Longitudinals of length 2.5 meters and spacings of 1.0 meter. In order to provide a wide overview of the trends between ABS and LRFD for these calculations, various sizes and spacings were chosen for illustration purposes, so that a whole range of comparisons could be represented in a short space. It was felt that this was a reasonable approach, as the trend for comparison of ABS and LRFD results seemed similar throughout the range of values for size and spacing chosen. The following charts show both Load Case A and Load Case B with nominal pressures. The representative lengths and spacings chosen are 2.5m & 700mm, 3.5m & 850mm, and 4.5m & 1000mm, respectively. Also, the differences are shown for Bottom Longitudinals with and without effective struts.





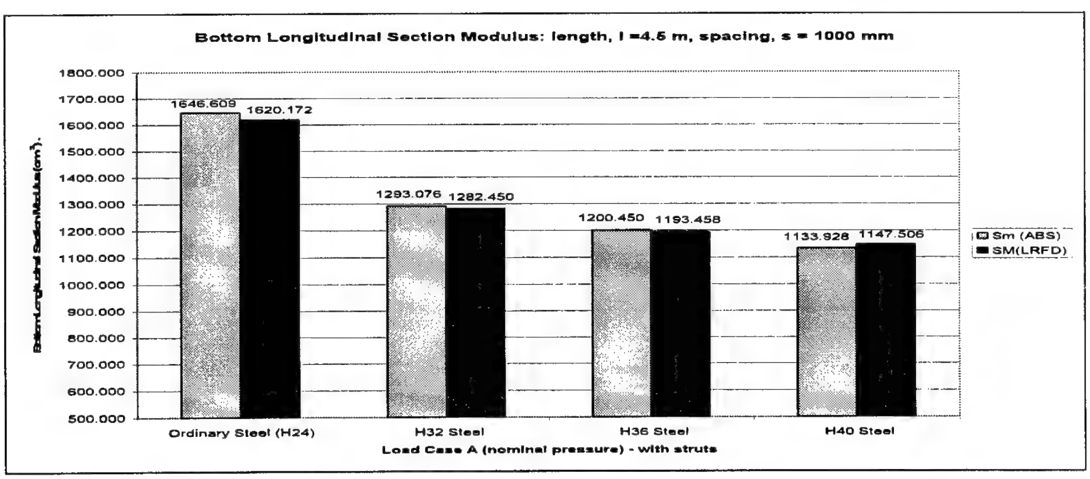
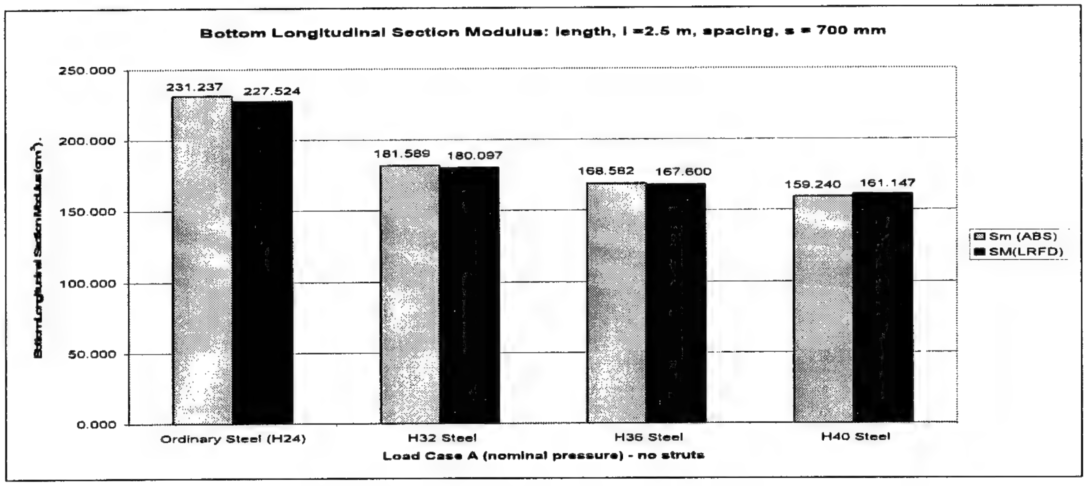
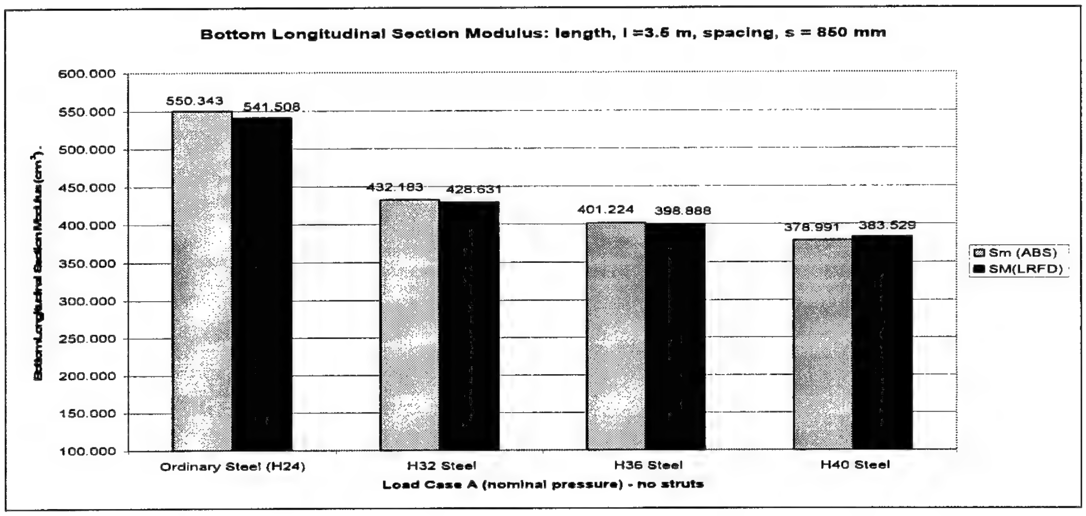


Fig. A-5-1 Bottom Longitudinal Section Modulus (Load Case A, w/ struts)





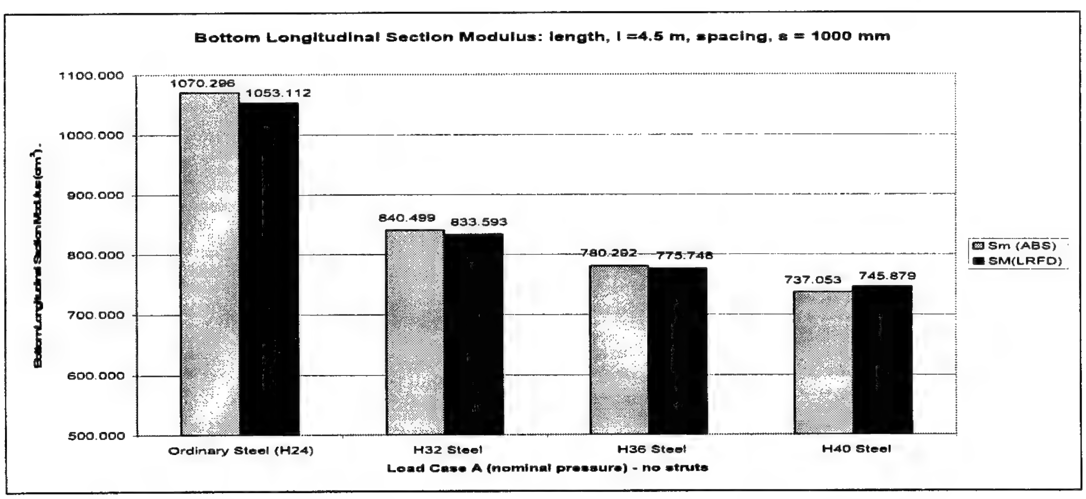
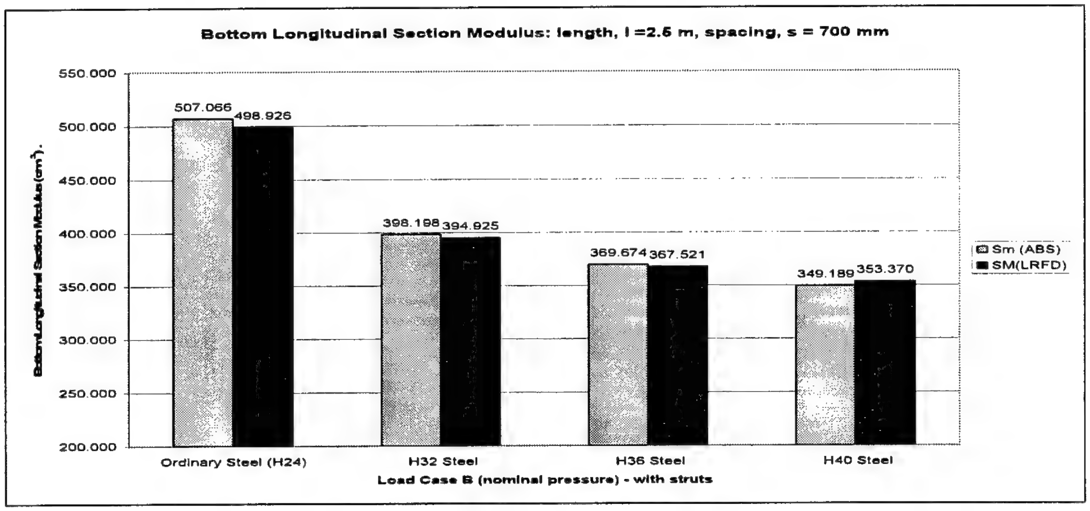
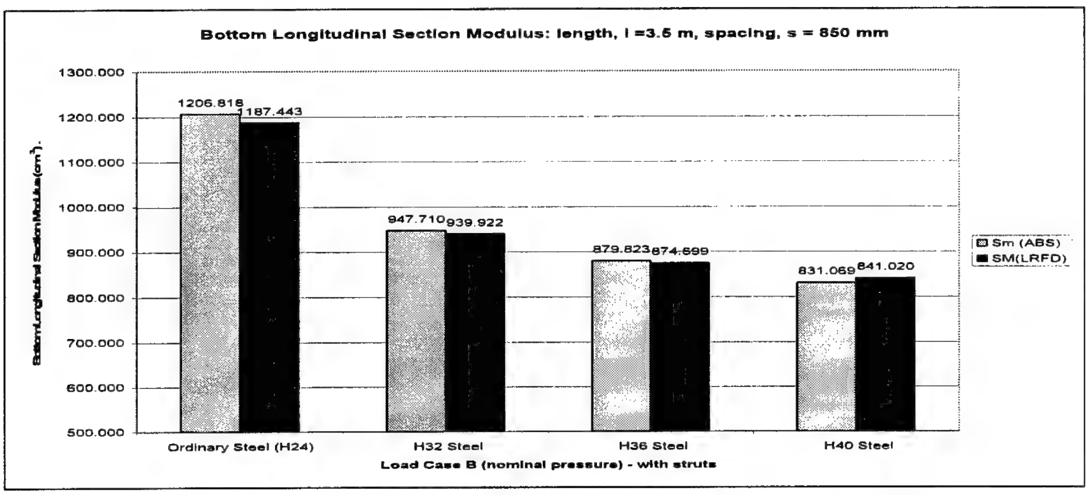


Fig. A-5-2 Bottom Longitudinal Section Modulus (Load Case A, w/o struts)





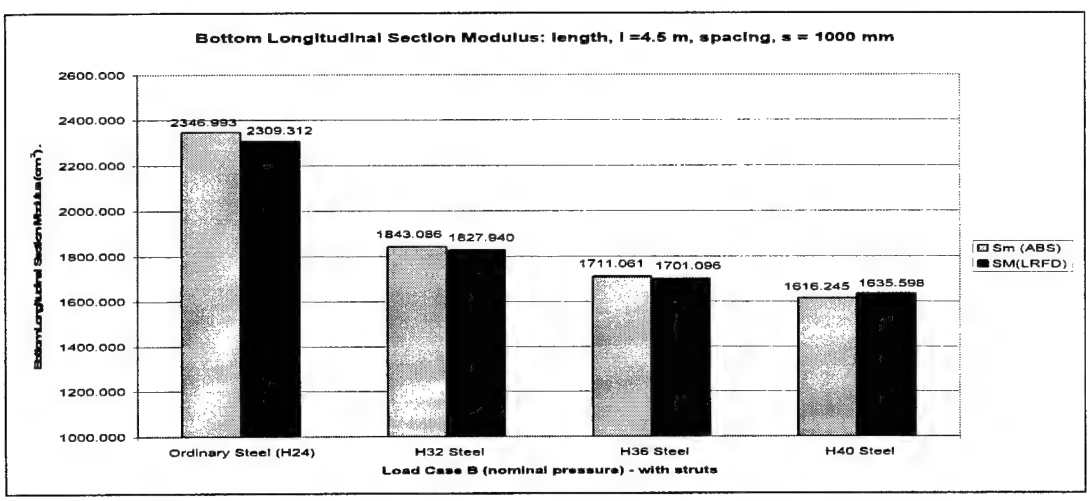
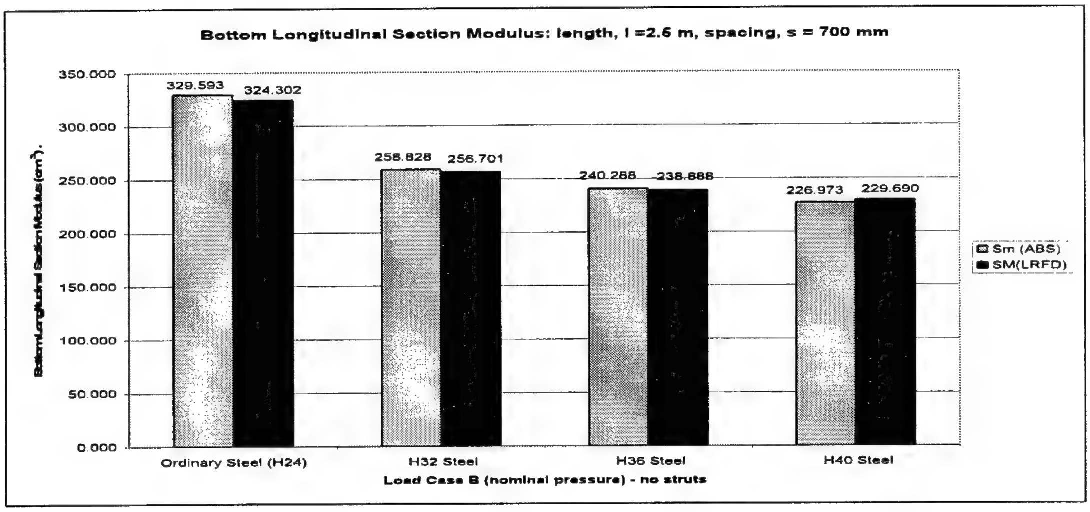
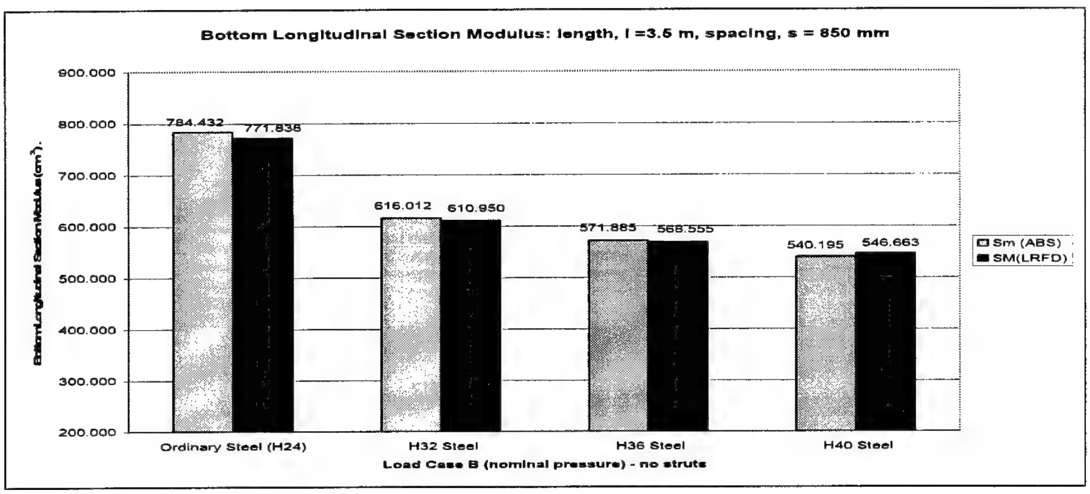


Fig. A-5-3 Bottom Longitudinal Section Modulus (Load Case B, w/ struts)





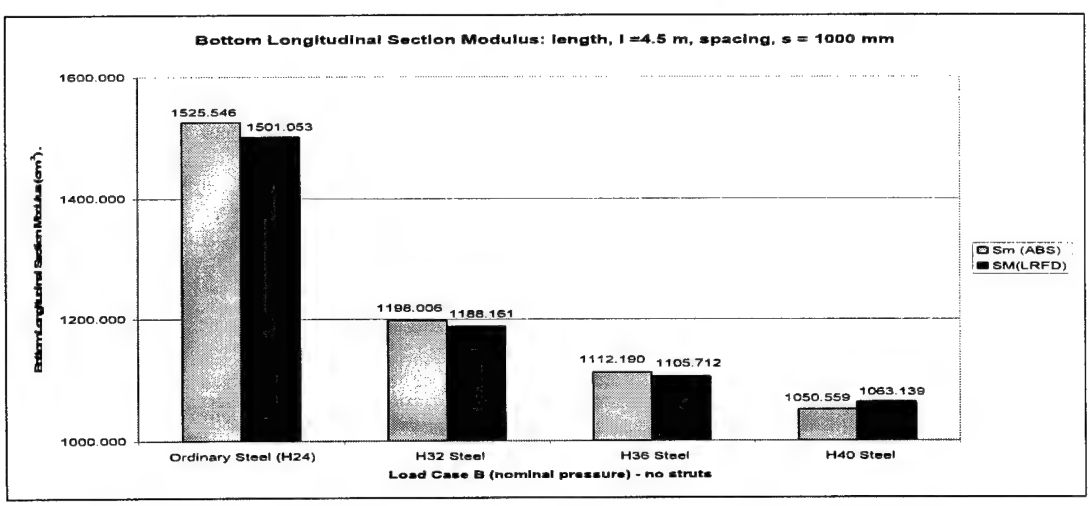


Fig. A-5-4 Bottom Longitudinal Section Modulus (Load Case B, w/o struts)

Appendix 6

Hull Section Modulus Comparisons

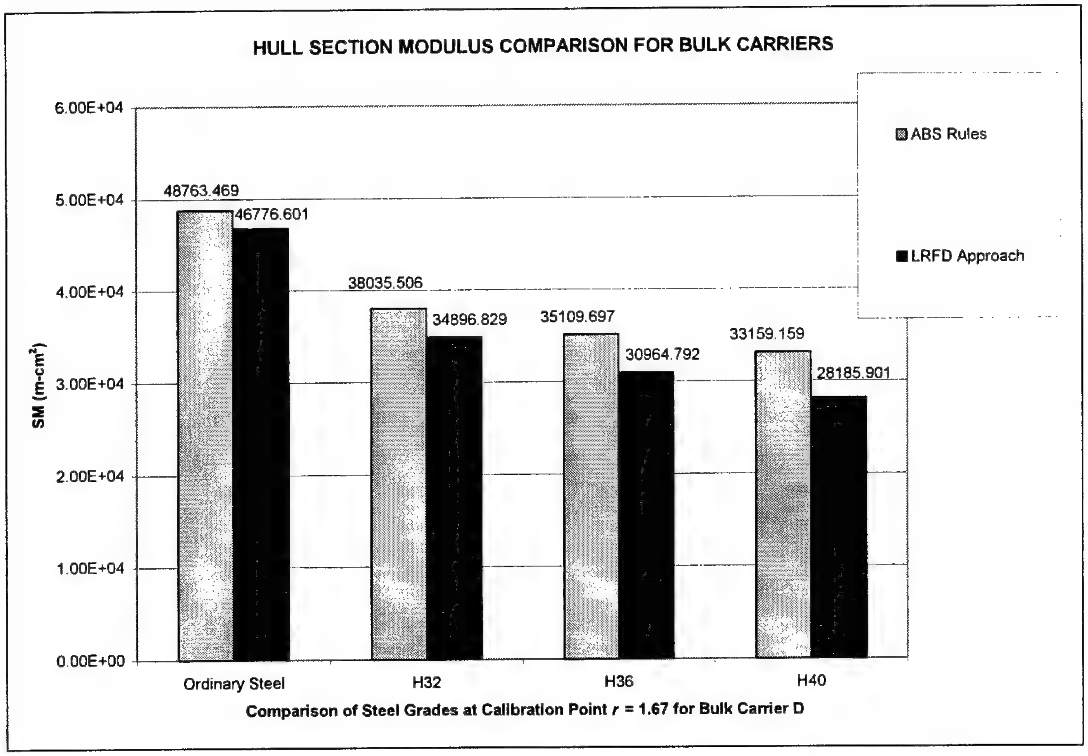
The partial safety factors used in the calculation of the LRFD Hull Section Modulus are shown in Table A-6-1 below. The r values between the highlighted areas are the Wave Bending Moment to Still Water Bending Moment ratios for the sample Bulk Carriers D, E, and F respectively (details of these ships are found in Appendix 1).

r=1.67 Calibration Point						
r = Mw/Ms	1.2	1.325	1.4	1.421	1.512	1.6
$\gamma 1$	0.826	0.806	0.794	0.791	0.781	0.770
$\gamma 2$	1.638	1.661	1.675	1.678	1.690	1.702
φ	1.001	1.004	1.006	1.007	1.009	1.011
r=2.0 Calibration Point						
r = Mw/Ms	1.2	1.325	1.4	1.421	1.512	1.6
$\gamma 1$	0.823	0.804	0.793	0.790	0.780	0.769
$\gamma 2$	1.595	1.617	1.630	1.633	1.645	1.656
φ	1.005	1.009	1.011	1.011	1.013	1.015
Note: Highlighted Values are direct from Tables of Mansour (2002)						

Table A-6-1 Partial Safety Factors for LRFD Calculations of Hull Section Modulus

Earlier in the text, the comparison for was made between all four steels for Bulk Carrier D. The next three figures show these comparisons for Carrier D (shown again for convenience), and also for Carriers E and F respectively.

Following the comparison of all steel grades for each ship, the comparisons are made between each ship's hull section modulus for each individual steel grade.



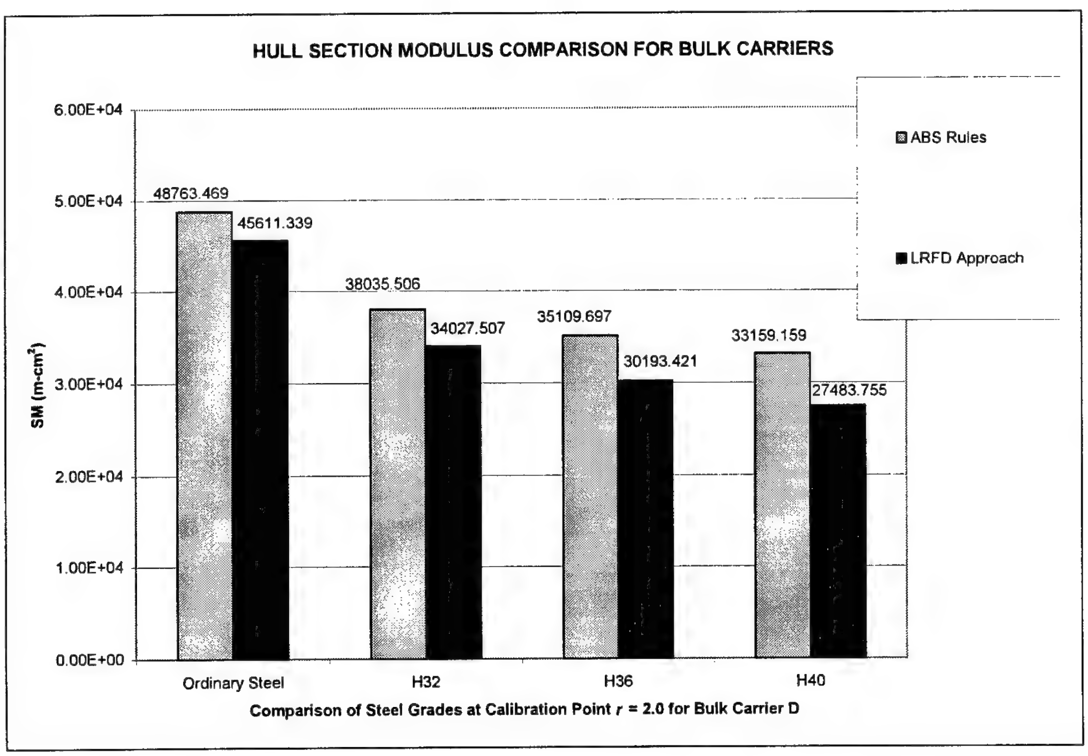
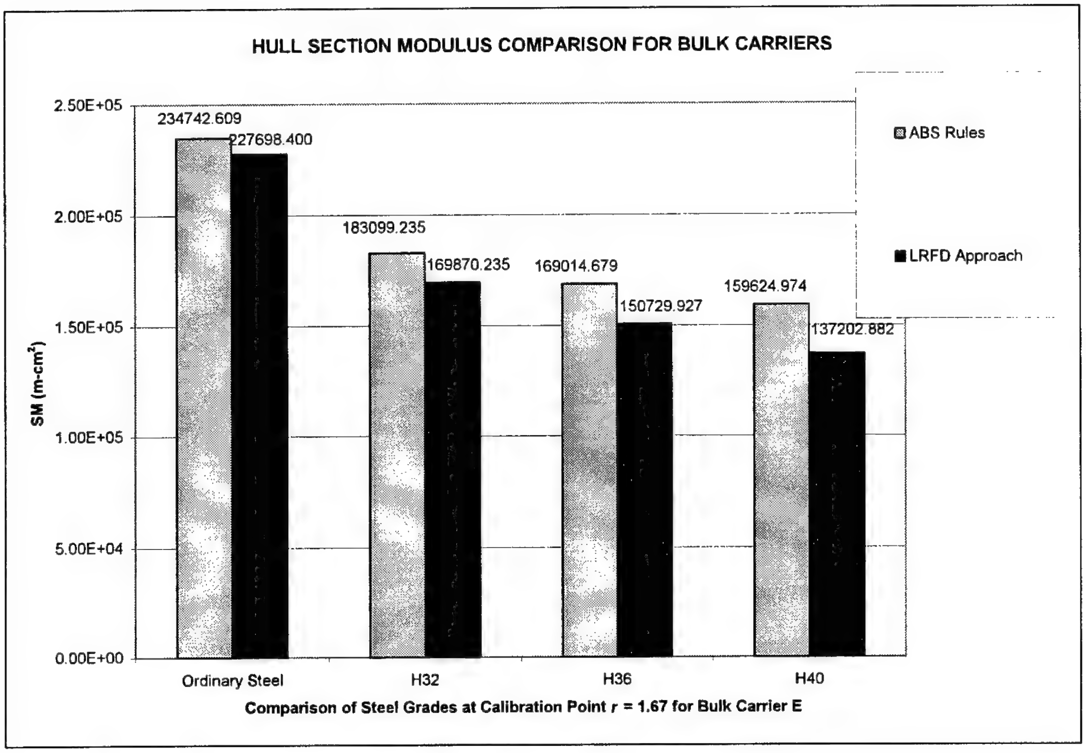


Fig.A-6-1 Hull section Modulus for Bulk Carrier D: a) r = 1.67, b) r = 2.0



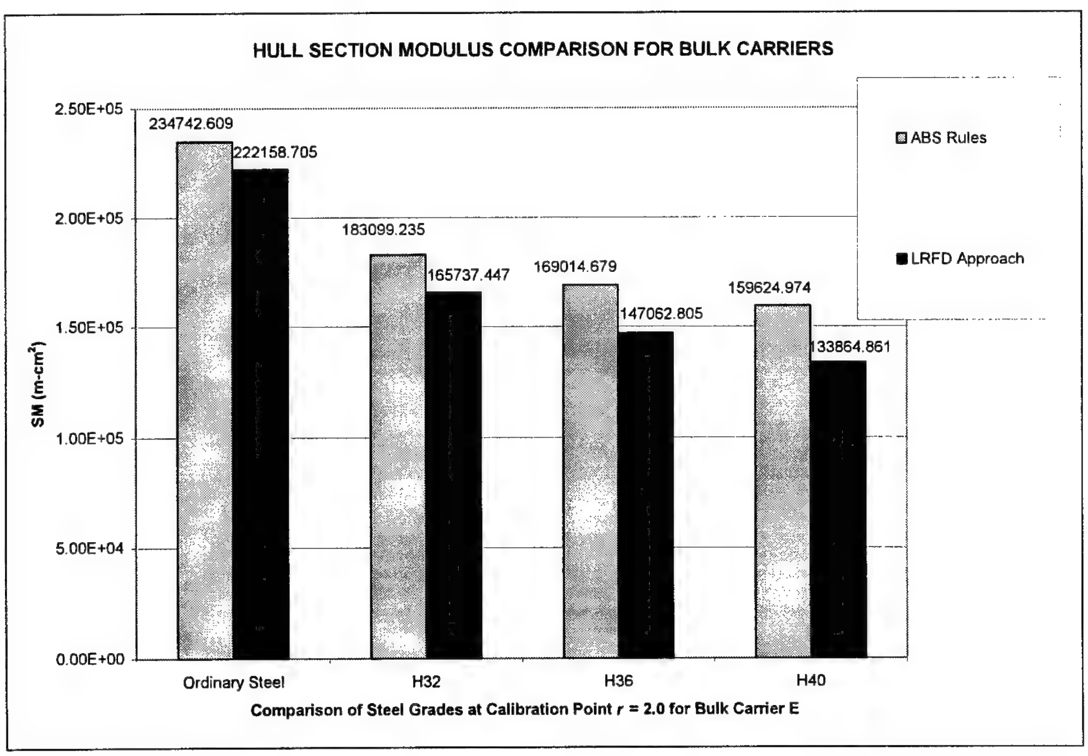
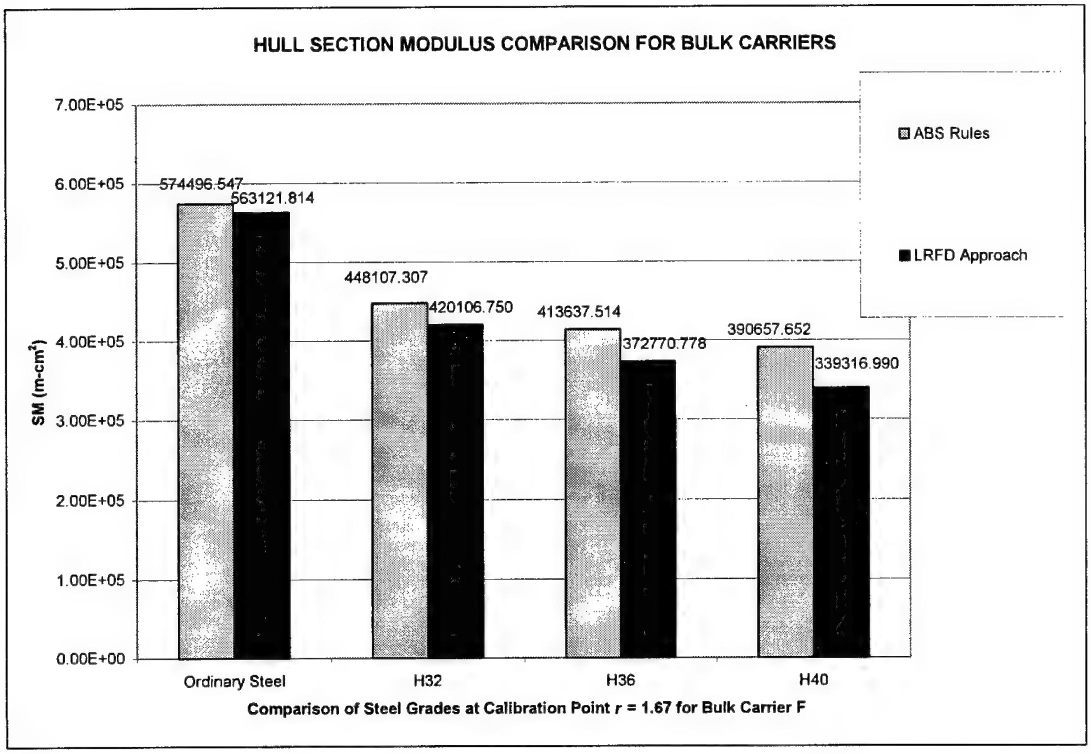


Fig.A-6-2 Hull section Modulus for Bulk Carrier E: a) r = 1.67, b) r = 2.0



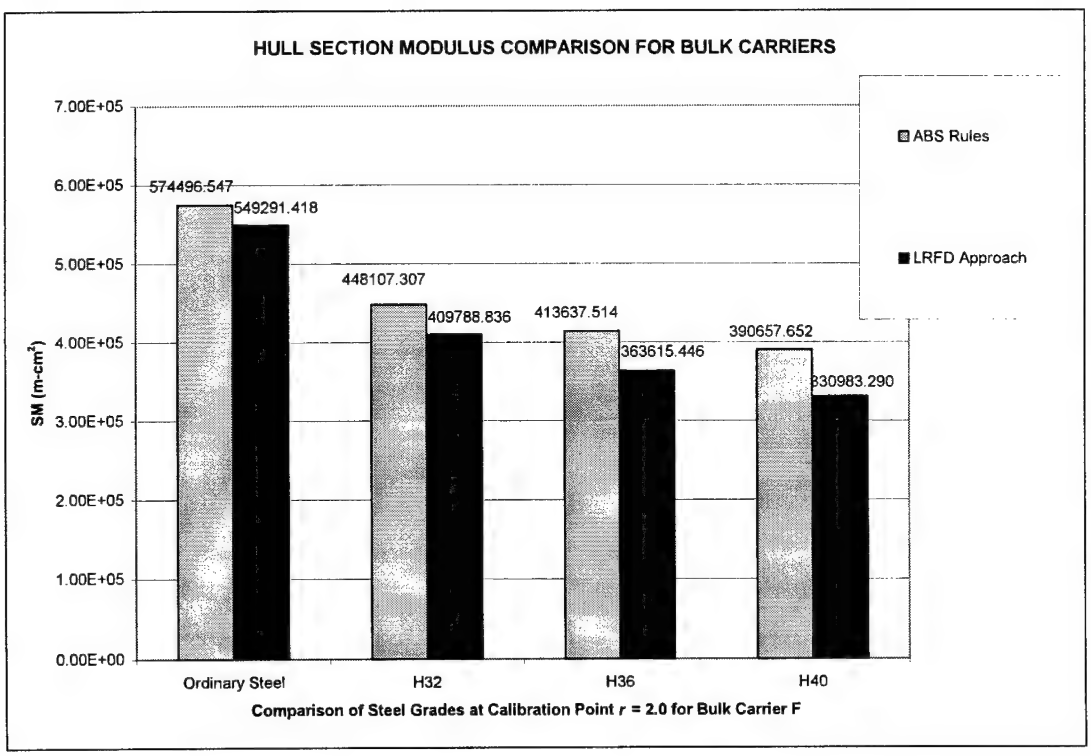
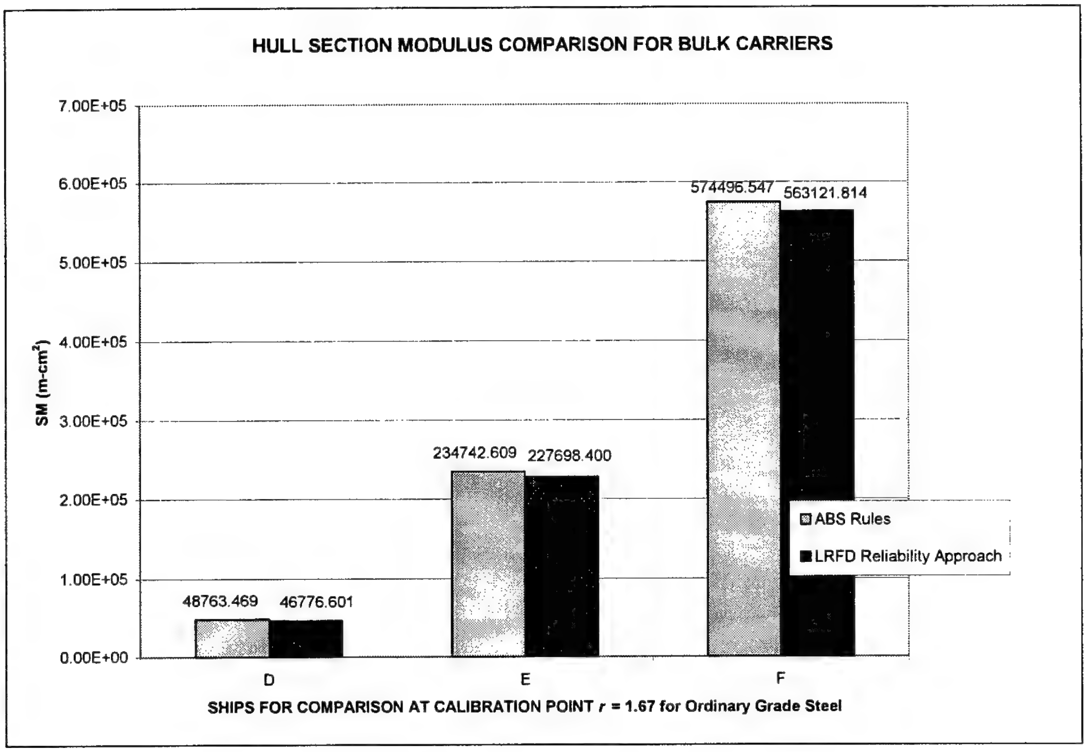


Fig.A-6-3 Hull section Modulus for Bulk Carrier F: a) r = 1.67, b) r = 2.0



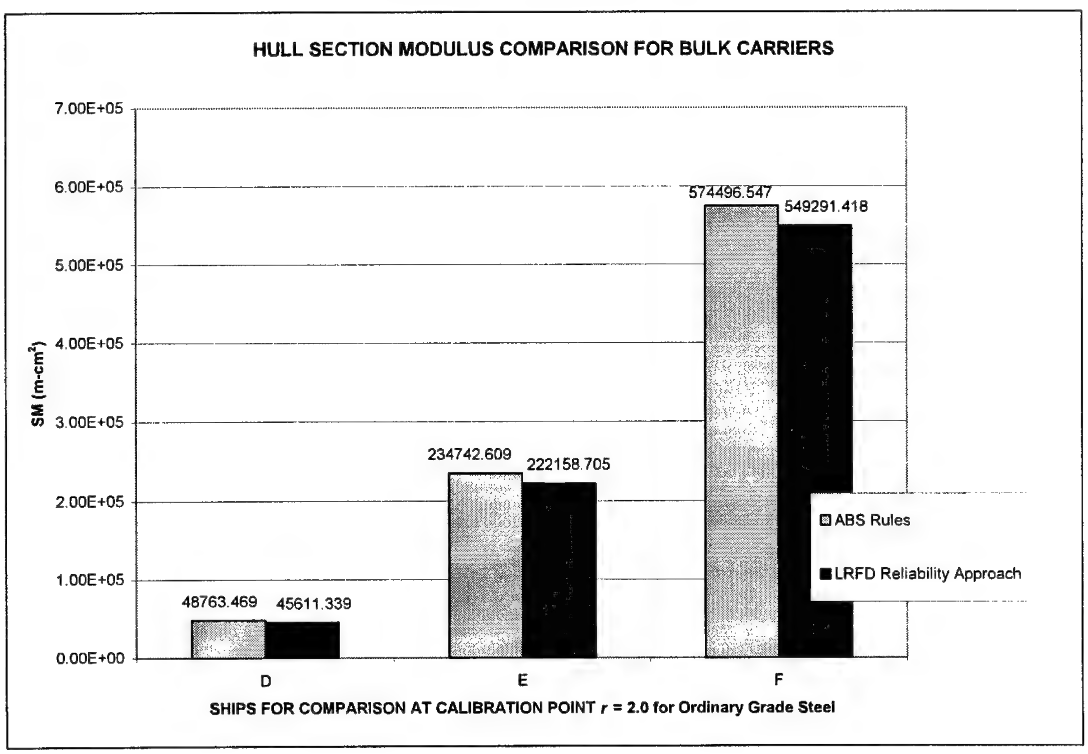
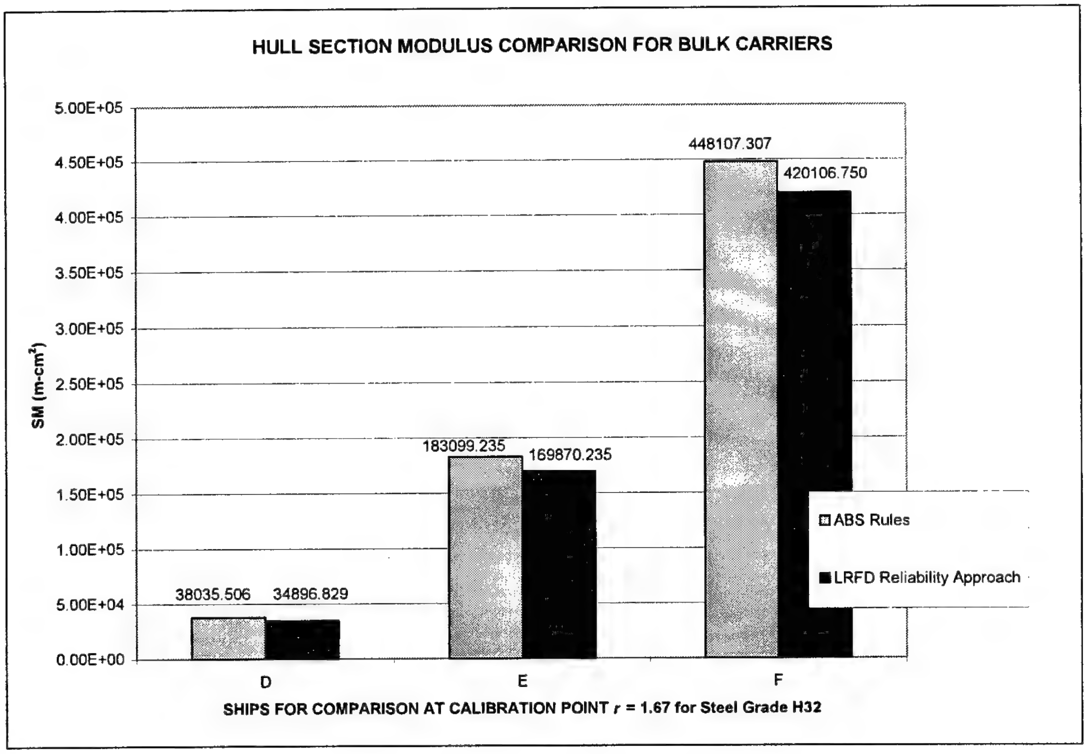


Fig.A-6-4 Hull section Modulus for Ordinary (H24) Steel: a) r = 1.67, b) r = 2.0



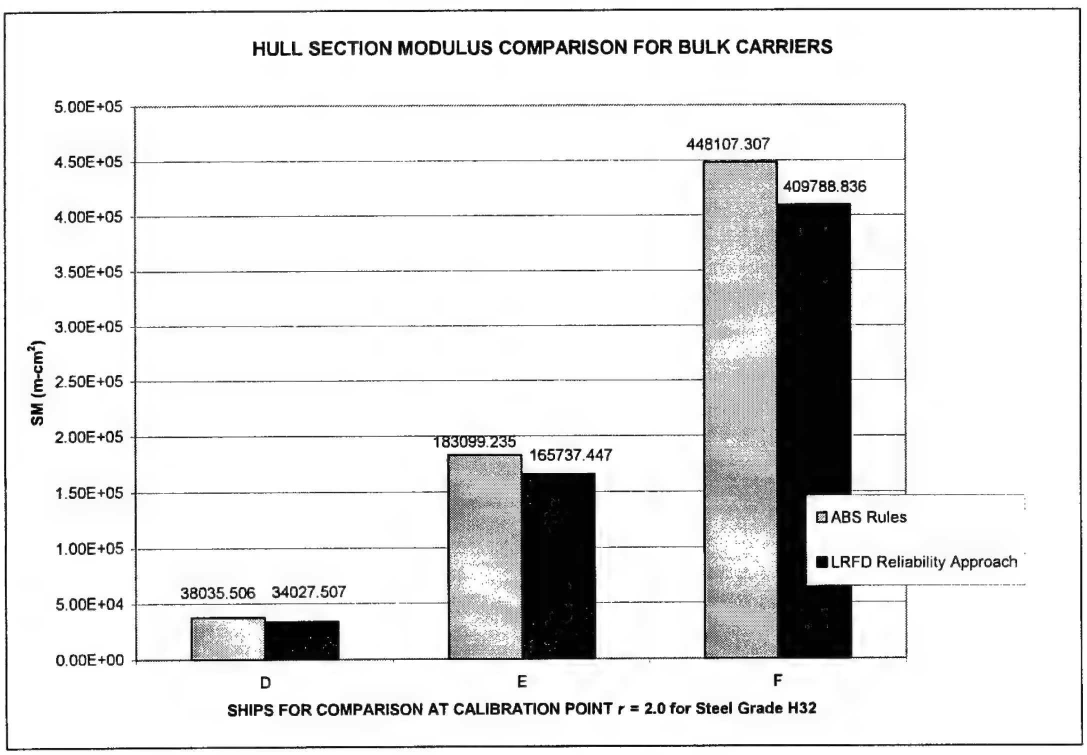
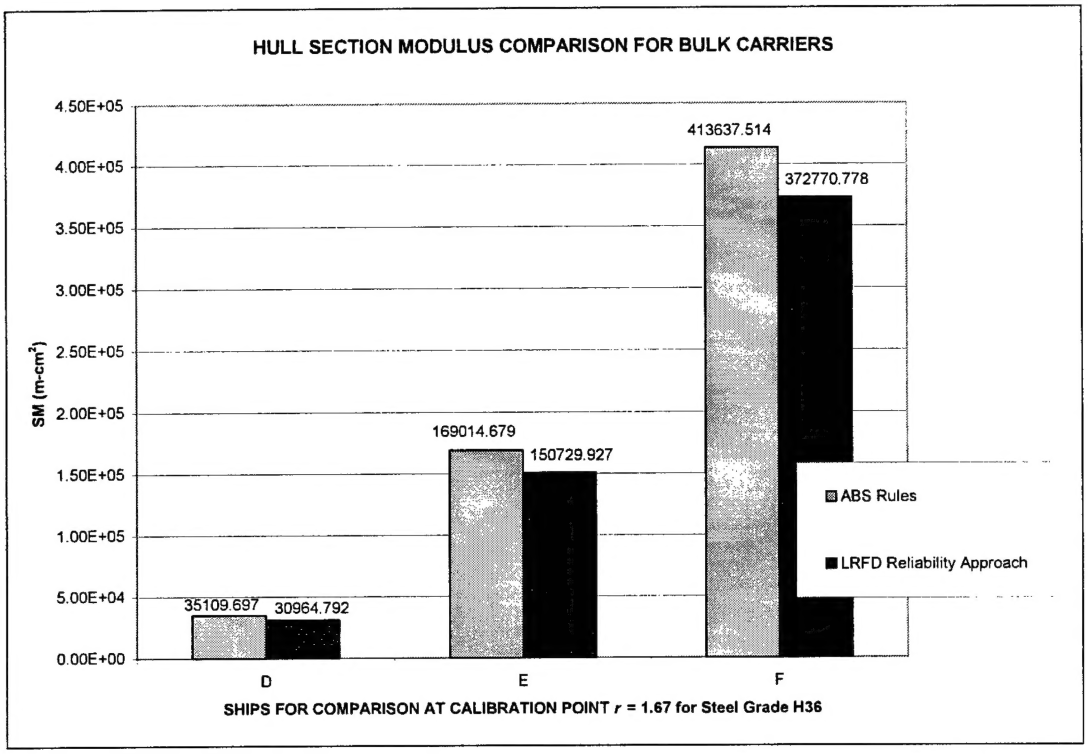


Fig.A-6-5 Hull section Modulus for Grade H32 Steel: a) r = 1.67, b) r = 2.0



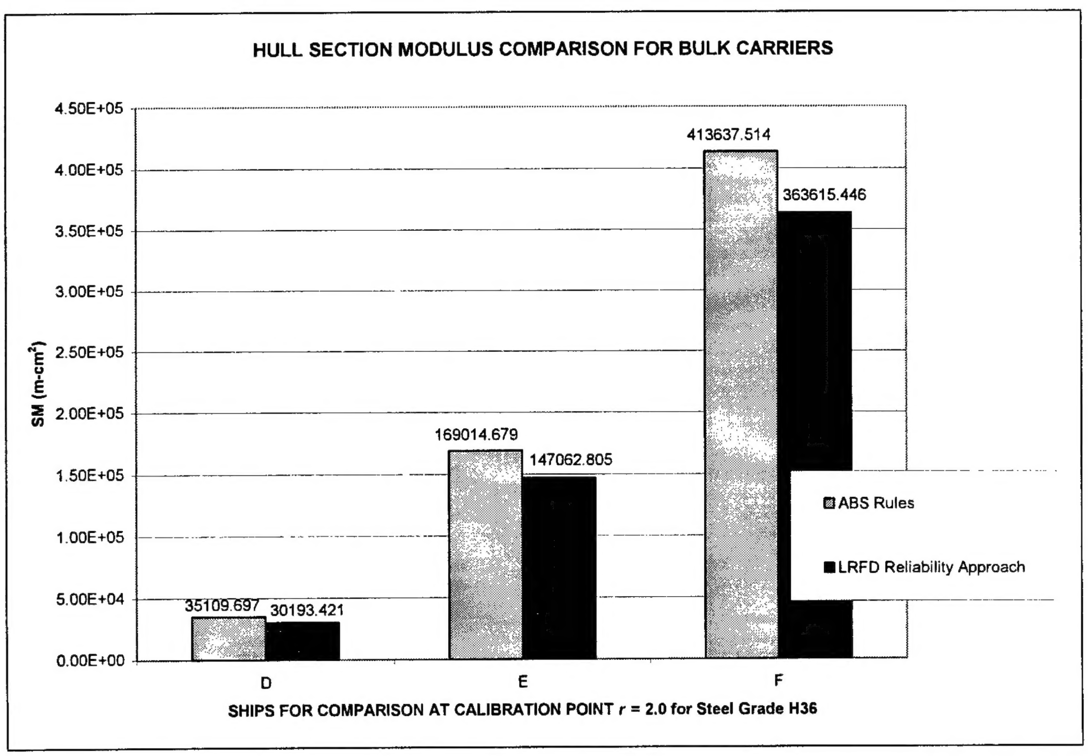
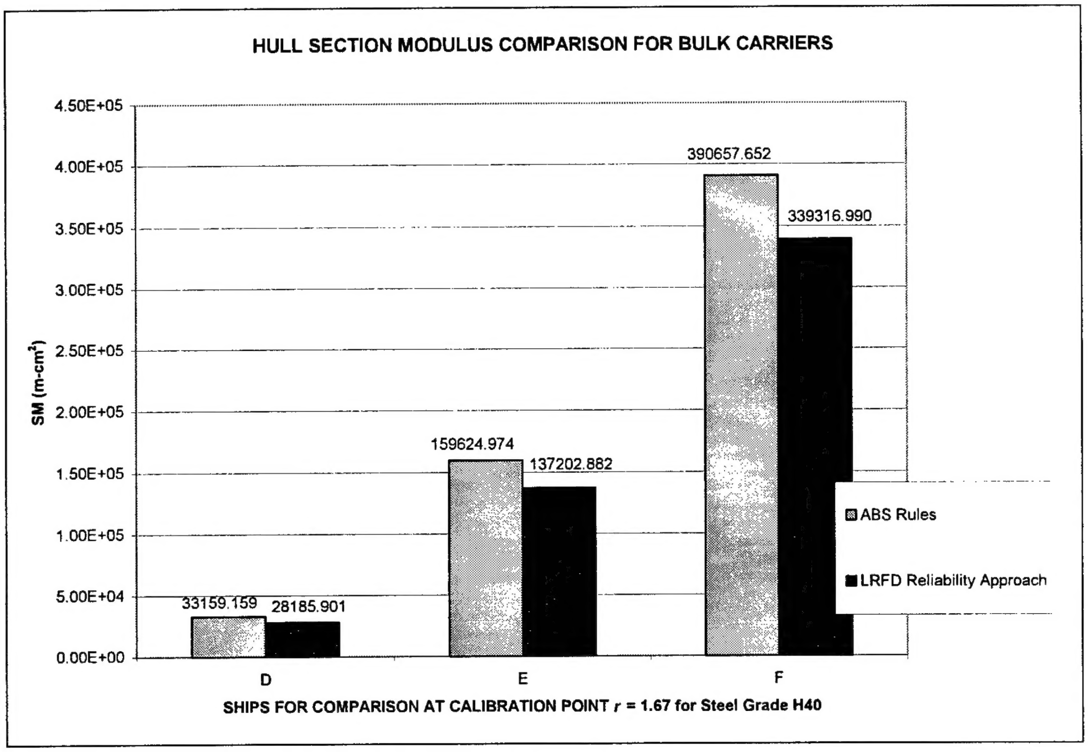


Fig.A-6-6 Hull section Modulus for Grade H36 Steel: a) r = 1.67, b) r = 2.0



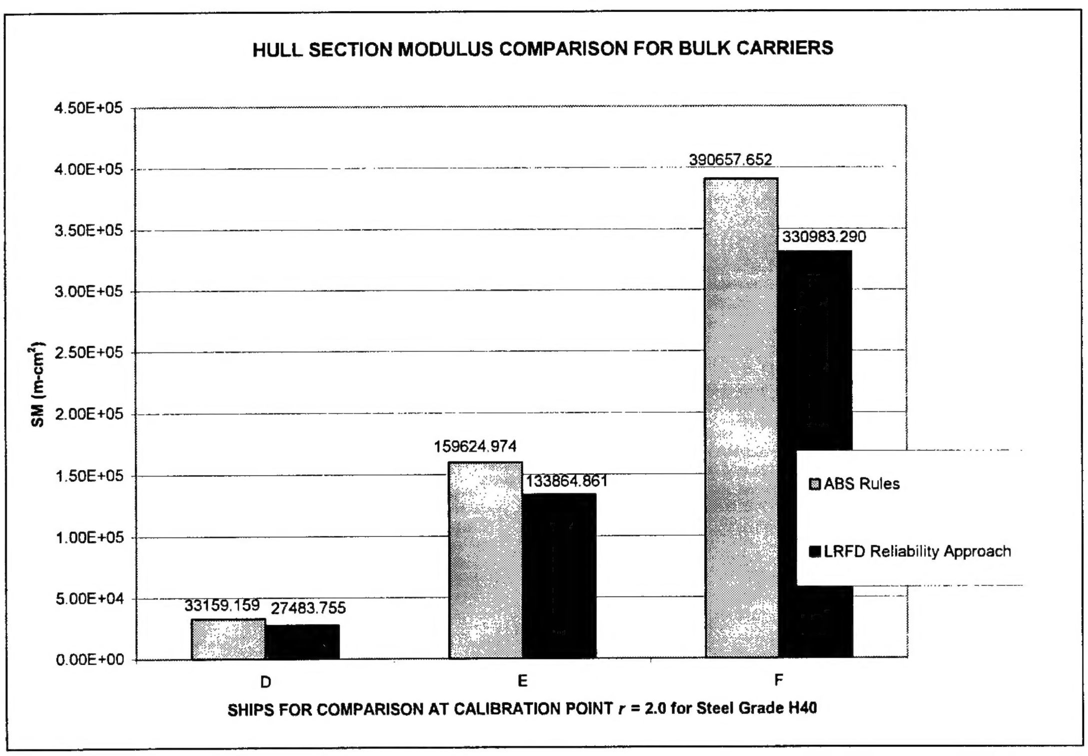


Fig.A-6-7 Hull section Modulus for Grade H40 Steel: a) r = 1.67, b) r = 2.0

Appendix 7

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